

Occupational heat stress and the role of wearable cooling interventions: A systematic review and meta-analysis of physiological and perceptual outcomes

by Ankit Sheth, MBBS, MD,^{1,*} Ankit Viramgami, MBBS, MD,^{1,*} Mahendra Thakor, MBBS, MD,¹ Bhavesh Modi, MBBS, MD,¹ Bhavanishankara Bagepally, MBBS, PhD,² Ananya Kar, MSc,¹ Ekta Ram, MPH,¹ Anuj Dave, MPH,¹ Rakesh Balachandar, MBBS, PhD³

Sheth A, Virmagami A, Thakor M, Modi B, Bagepally B, Kar A, Ram E, Dave A, Balachandar R. Occupational heat stress and the role of wearable cooling interventions: A systematic review and meta-analysis of physiological and perceptual outcomes. *Scand J Work Environ Health* – online first.

Objective Occupational heat stress, driven by high ambient temperatures, humidity, and radiant heat impairs health, safety, and productivity. Among the interventions for mitigating heat strain, wearable cooling technologies [eg, water/ice, phase-change materials (PCM), ventilated/evaporative garments] is increasingly used, but their comparative effectiveness remains unclear. This systematic review aimed to evaluate the effectiveness of wearable cooling intervention on physiological and perceptual outcomes during heat exposure.

Methods Adhering to PRISMA guidelines (PROSPERO: CRD42025631559), we searched PubMed, Embase, and Scopus (February 2026) for randomized or non-randomized intervention trials among workers or acclimatized adults. Data were extracted as mean/standard deviation (or transformed equivalents) and pooled using random-effects meta-analysis. Heterogeneity (I^2), small-study effects (Egger's test) and sensitivity/subgroup analyses of cooling modalities were performed. Risk of bias (RoB 2, ROBINS-I) and certainty (GRADE) were assessed.

Results Sixty-nine studies were included in our review. Post-exposure, wearable cooling significantly reduced rectal temperature [mean difference (MD) -0.24°C ; 95% confidence interval (CI) -0.37 – -0.1 ; $I^2=43.91\%$], gastrointestinal temperature (MD -0.26°C ; -0.52 – -0.001 ; $I^2=98.13\%$), skin temperature (MD -1.14°C ; -1.85 – -0.42 ; $I^2=96.56\%$), and heart rate (MD -7.69 bpm; -11.22 – -4.15 ; $I^2=73.19\%$). Egger's tests suggested possible small-study effects for skin temperature and heart rate but not for core temperatures. Subgroup analyses indicated more consistent benefits with water/ice and PCM garments. Overall certainty ranged from low to very low due to risk of bias, inconsistency, and imprecision.

Conclusions Wearable cooling attenuates physiological heat strain and improves thermal comfort, particularly via water/ice and PCM systems. Given high heterogeneity and low certainty, adequately powered, standardized, head-to-head trials are needed.

Key terms core body temperature; heart rate; heat strain; occupational heat strain; phase-change material; physiological outcome.

Occupational heat stress is a major risk factor for adverse health outcomes, reduced productivity, and increased injury risk in hot working environments. It refers to the physiological heat strain experienced in workplace settings, particularly among workers exposed to high ambient temperatures (1). These integrated thermophysiological responses manifest as elevations in core and skin temperatures, cardiovascular load,

sweat loss, and perceptual discomfort. Heat strain may arise from extreme ambient temperatures, high humidity, radiant industrial heat, and the use of personal protective equipment (PPE), which can further limit heat dissipation. Climate change amplifies these risks and disproportionately affects outdoor and physically demanding occupations.

Occupational heat exposure is associated with both

* both authors equally contributed and regarded as first authors

¹ Indian Council of Medical Research (ICMR) – National Institute of Occupational Health, Ahmedabad, India.

² ICMR – National Institute of Epidemiology, Chennai, India.

³ ICMR – Regional Occupational Health Centre, Bengaluru, India.

Correspondence to: Rakesh Balachandar, MBBS, PhD, Scientist-, ICMR-Regional Occupational Health Centre, Bengaluru-562110, India. [E-mail: rakesh.bal@icmr.gov.in; balachandar.rakesh@gmail.com]. ORCID: <https://orcid.org/0000-0002-9940-4878>

acute and chronic adverse outcomes, including cardiovascular and renal strain, fatigue, dehydration, impaired cognitive and physical performance, heat-related illnesses, reduced productivity, and increased injury risk (2). At the population level, heat stress is increasingly recognized as a major occupational health and economic challenge. By 2030, burden estimates include 0.9 million work-life years lost to heat-related mortality and around 70 million work-life years lost to reduced productivity, with larger impacts expected in low- and middle-income countries (LMIC) and in informal sectors lacking engineering controls or social protections (1).

To mitigate occupational heat stress, cooling interventions can be implemented at individual, organizational, and policy levels. Although engineering and administrative controls remain the foundation of heat stress prevention, they are often impractical or insufficient in many real-world work settings, particularly for mobile workers, outdoor laborers, or personal protective equipment (PPE)-dependent occupations. In such contexts, wearable cooling systems have been proposed as practical adaptation strategies because they are portable and can be used across diverse work environments. These technologies vary in both body coverage, ranging from localized neck or head devices to full-body systems, and cooling modality, including ice-based, cold-water, phase-change material (PCM), ventilated, and evaporative garments (3). Despite their differences in design, all aim to reduce physiological heat strain by enhancing heat dissipation, reducing cardiovascular burden, and improving thermal comfort during heat exposure.

From a mechanistic perspective, wearable cooling systems operate through two main thermoregulatory pathways. Contact-based systems – such as ice packs, cold-water garments, and PCM vests – absorb heat directly. PCM materials are designed to melt at pre-defined temperatures, allowing them to absorb latent heat and provide more sustained and controlled cooling than ice while reducing the risk of cold-related discomfort or injury. Ventilated and evaporative systems, by contrast, promote convective and evaporative heat loss through airflow or moisture-wicking fabrics, sometimes supported by fans or breathable materials. While various cooling interventions exist, wearable cooling systems have emerged as particularly practical solutions for workers exposed to heat.

Previous narrative reviews and small-scale studies have reported physiological benefits of wearable cooling, but the evidence remains fragmented, limited to specific occupations, and inconsistent with regard to outcome measures. Comparative evidence across wearable cooling modalities is limited, and no comprehensive systematic review and meta-analysis has synthesized findings across these interventions, directly compared their effectiveness, or evaluated the certainty of evi-

dence using the GRADE (Grading of Recommendations Assessment, Development, and Evaluation) approach. Therefore, this systematic review aimed to evaluate the extent to which wearable cooling interventions improve physiological and perceptual outcomes among workers or previously acclimatized participants and, secondarily, to compare interventions using network meta-analysis.

Methods

The study followed the PRISMA (Preferred Reporting Items of Systematic Reviews and Meta-Analyses) Guidelines, and was registered in PROSPERO (ID: CRD42025631559) (4). We included interventional trials (randomized or non-randomized) assessing wearable cooling effectiveness in mitigating heat-stress effects among workers or acclimatized participants. Searches of Embase, Scopus, and PubMed were performed in May 2024 and later updated through 24 February 2026 using PICO-based terms optimized for sensitivity and precision; bibliographies of included studies were screened. Preclinical studies, reviews, commentaries, editorials, and methodological articles were excluded. Full search strategies are in supplementary materials (www.sjweh.fi/article/4294), table 1(a–c).

Screening and reviewing of studies

Screening and reviewing procedures followed previously described methods (5, 6). Screening used the Rayyan platform (7). Three authors independently reviewed full texts and three additional authors extracted data, with discrepancies resolved by consensus.

Data collection, extraction, analysis and management

Data collection and extraction methods have been described earlier (5, 6). Data extraction captured study details, participant characteristics, intervention descriptions, trial conditions, and outcomes. Data were managed using Google docs.

Central tendency values and dispersion measures were extracted from all included studies. Where only graphical data were available (8–11) WebPlotDigitizer was used (12). Non-standard units were converted to standard units and mean/standard deviation (SD) derived using accepted transformations (13). For multi-arm studies, grand means were calculated according to guidance (14). Pooled mean differences [95% confidence interval (CI)] were estimated using the generic inverse variance method and applied random-effects models anticipating heterogeneity. Results are reported for randomized and non-randomized controlled trials by outcome.

Assessment of the risk of bias and certainty of evidence- Risk of bias was assessed with RoB 2 for randomized (including cluster and crossover) trials (15) and for non-randomized studies were assessed using the “Risk of Bias in Non-Randomized Studies of Interventions” (ROBINS-I) tool (16). Certainty of evidence was graded using the GRADE framework (17)

Heterogeneity, sensitivity and subgroup analysis

The assessment and interpretation of heterogeneity among studies, subgroup analyses (if >2 primary studies were available in the particular subgroup) and sensitivity (if >9 primary studies were available) were performed using conventional steps (5, 6). Mean difference and heterogeneity (I^2) changes as compared to the larger pooled estimate were noted to interpret the influence of the subgroup. Leave-one-out sensitivity analyses assessed the influence of single studies (18). $I^2 > 25\%$ or Cochran’s Q $P < 0.10$ were considered evidence of heterogeneity. Funnel plots and contour-enhanced funnel plots explored bias when >10 studies were available (19).

Comparison of interventions

The cooling technologies broadly include those that use either water or ice, PCM, ventilation or evaporation of sweat and other approaches that do not fit within these descriptions such as radiance reflectors.

Data were downloaded and cleaned using Microsoft Excel and analyzed using Stata version 16 (StataCorp, College Station, TX, USA) and JASP version 0.95.1 (Team J). Two-sided $P < 0.05$ was considered statistically significant except for the subgroup analysis and heterogeneity test, wherein $P < 0.10$ was regarded as significant.

Results

Database searches returned 8591 citations; 69 articles met the inclusion criteria (figure 1).

The studies involved a diverse range of worker populations with known exposure to heat stress environments either due to environmental conditions – such as construction and outdoor industrial workers, soldiers and

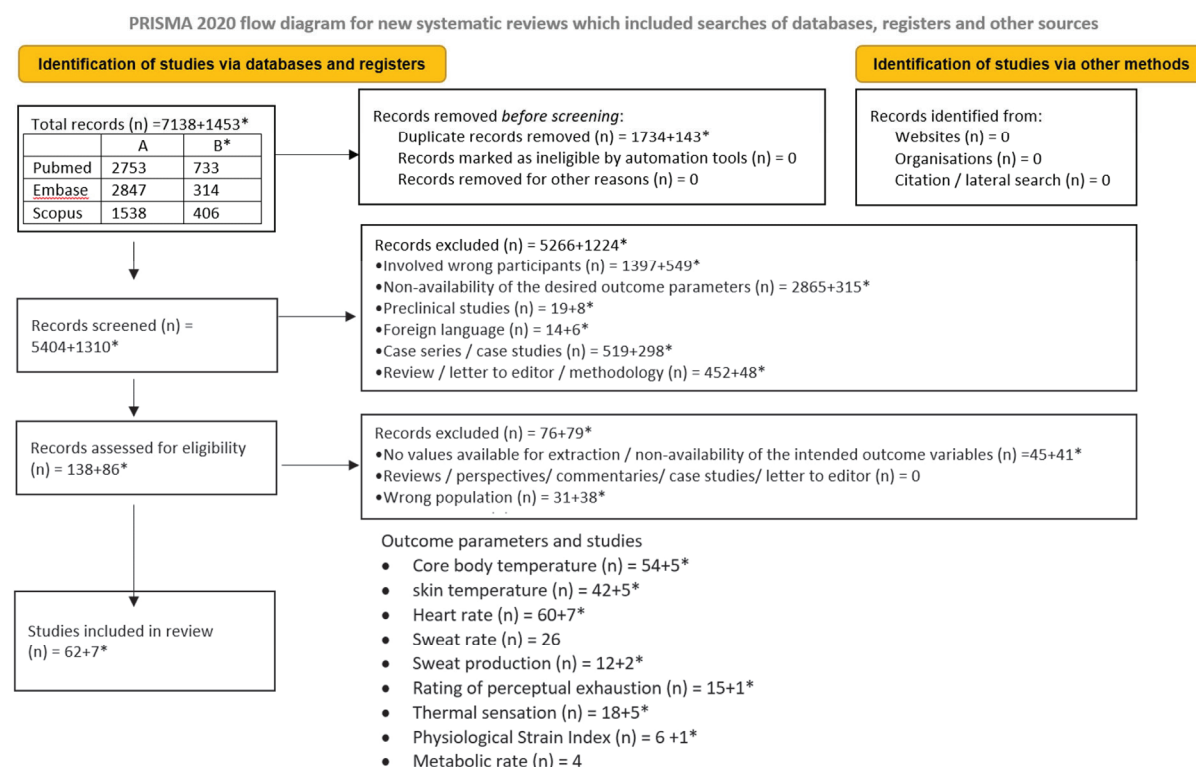


Figure 1. PRISMA flow chart describing the number of citations included and excluded at various stages. *The initial search was performed for studies published until 14 May 2024. Later, prior to publication, the search was updated to include studies published by 24 February 2026. From: Page MJ, McKenzie JE, Bossuyt PM, Boutron I, Hoffmann TC, Mulrow CD, et al. The PRISMA 2020 statement: an updated guideline for reporting systematic reviews. *BMJ* 2021;372:n71. doi: 10.1136/bmj.n71. For more information, visit: <http://www.prisma-statement.org>.

farmers – or virtue of wearing personal protective equipment (PPE), such as the firefighters, medical personnel, and chemical and radiation protective covers. Details of individual studies are presented in supplementary table 2. To summarize the salient observations, a majority of studies involved participants aged 20–40 years, and most enrolled male participants (>70% of trials).

The heat stress exposure conditions varied widely. Many trials (N=53) were conducted in climate-controlled chambers (or the equivalent) simulating environmental temperatures from 30–48°C, with relative humidity ranging 20–75%. Others (N=16) were conducted in real-world occupational settings, including construction sites, steel plants, agriculture fields, restaurant kitchen and healthcare facilities, including COVID-19 wards. The duration of heat exposure typically ranged from 30 minutes to >2 hours, often involving treadmill walking, simulated task performance, or real-time occupational activities.

Most studies employed randomized controlled cross-over designs, facilitating within-subject comparisons and increasing the reliability of findings. Therefore, the sample size in the majority of the studies was within 15. While, a few employed parallel-group randomized controlled trials (RCT) or non-randomized crossover designs. A diverse array of cooling strategies was evaluated. PCM-based cooling vests were commonly tested and typically worn over the torso during work activities, as demonstrated in studies by Bach et al (20, 21), Chicas et al (22), House et al (23), Maley et al (24), Udayraj et al (25) and Zhao et al (26). Liquid cooling garments (LCG), using water circulated through embedded tubing, were assessed in studies such as Aljaroudi et al (27) and Kim et al (28, 29), with some variants offering extended coverage to the limbs and head. Ice-based cooling methods, including ice vests and ingestion of ice slurry, were used either as pre-cooling or during work exposure in studies like (8, 24). Other studies incorporated fans or

Table 1. Risk of bias assessment for randomized controlled trials – crossover studies.

Studies	Randomization process in a crossover trial	Selection of reported result in a crossover trial	Deviations from intended intervention in a crossover trial		Missing outcome data in a crossover trial	Outcome measurement	Selection of reported result in a crossover trial	Overall study-wise prediction
			For effect of assignment to intervention	For effect of adhering to intervention				
Bach et al, 2024 (21)	Low	Low	Low	Low	Low	Low	Low	Low
Ciuha et al, 2023 (9)	Low	Low	Low	Low	Low	Low	Low	Low
Bonell et al, 2021 (8)	Low	Low	Low	Low	Low	Low	Low	Low
Ioannou et al, 2021 (43)	Low	High	Low	Low	Low	Low	Low	High
Maley et al, 2020 (24)	Low	Low	Low	Low	Low	Low	Low	Low
Aljaroudi et al, 2020 (27)	Low	High	Low	Low	Low	Low	Low	High
Kim et al, 2020 (11)	Low	Low	Low	Low	Low	Some concern	Low	Some concern
Bach et al, 2019 (20)	Low	Low	Low	Low	Low	Low	Low	Low
Udayraj et al, 2019 (25)	Low	Low	Low	Low	Low	Low	Low	Low
McQuerry et al, 2018 (75)	Low	Low	Low	Low	Low	Low	Low	Low
Maley et al, 2017 (59)	Low	Low	Low	Low	Low	Some concern	Low	Some concern
Sefton et al, 2016 (32)	Low	Low	Low	Low	Low	Low	Low	Low
O'Hara et al, 2016 (80)	Low	High	Low	Low	Low	Low	Low	High
Chan et al, 2016 (54)	Low	Low	Low	Low	Low	Low	Low	Low
Teunissen et al, 2014 (76)	Low	High	Low	Low	Low	Some concern	Low	High
McLellan et al, 2013 (34)	Low	Low	Low	Low	Low	Low	Low	Low
House et al, 2013 (23)	Low	Low	Low	Low	Low	Low	Low	Low
Kim et al, 2011 (28)	Low	Low	Low	Low	Low	Some concern	Low	Some concern
Kim et al, 2011 (29)	Low	Low	Low	Low	Low	Low	Low	Low
Minett et al, 2011 (31)	Low	High	Low	Low	Low	Some concern	Low	High
Barr et al, 2011 (47)	Low	Low	Low	Low	Low	Some concern	Low	Some concern
Amorim et al, 2010 (81)	Low	Low	Low	Low	Low	Some concern	Low	Some concern
Zhang et al, 2010 (65)	Low	Low	Low	Low	Low	Some concern	Low	Some concern
Choi et al, 2008 (55)	Low	High	Low	Low	Low	Some concern	Low	High
Duffield et al, 2007 (72)	Low	High	Low	Low	Low	Some concern	Low	High
Smolander et al, 2004 (79)	Low	Low	Low	Low	Low	Some concern	Low	Some concern
Cotter et al, 2001 (87)	Low	Low	Low	Low	Low	Low	Low	Low
White et al, 1991 (62)	Low	High	Low	Low	Low	Some concern	Low	High
Wang et al, 2024 (38)	Low	High	Low	Low	Low	Low	Low	High
Byrne et al, 2023 (50)	Low	Low	Some concern	Low	Low	High	Low	High
Wang et al, 2023 (61)	Low	High	Low	Low	Low	Low	Low	High
Inoue et al, 2023 (78)	Low	High	Low	Low	Low	Some concern	Low	High
Mori et al, 2022 (60)	Low	Low	Low	Low	Low	Low	Low	Low
de et al, 2022 (57)	Low	Low	Low	Low	Low	Low	Low	Low
Yi et al, 2017 (64)	Low	High	Low	Low	Low	Some concern	Low	High
Chan et al, 2019 (77)	Low	High	Low	Low	Low	Low	Low	High
Sainiyom et al, 2026 (69)	Low	Low	Low	Low	Low	Some concern	Low	Some concern
Hutchins et al, 2025 (10)	Low	Low	Low	Low	Low	Some concern	Low	Some concern
Kaufman et al, 2025 (68)	Low	Low	Low	Low	Low	Some concern	Low	Some concern
Ciuha et al, 2024 (66)	Low	High	Low	Low	Low	Some concern	Low	High
Mansouri et al, 2024 (82)	Low	High	Low	Low	Low	Some concern	Low	High

special sweat wicking technology collectively termed as evaporative cooling technologies. Occasionally combinations of multiple technologies such as hybrid of PCM with air ventilation were investigated [eg, (9, 30)]. Localized cooling interventions, such as neck scarves, towels, or head cooling pads, were evaluated in settings where full-body systems were not feasible (31, 32). Notably, some of these interventions were investigated for its effectiveness while wearing a PPE.

The studies included in this systematic review were conducted across a wide range of geographical locations, reflecting a global effort to evaluate the effectiveness of cooling interventions for mitigating occupational heat stress. A substantial proportion of the evidence originates from high-income countries such as the United States [eg, (32, 33)], Canada (34), Australia (24, 31), Germany (35), and the United Kingdom (36). Several Asian countries, including Japan (37), South Korea (11) China (38), India (39–41) and Thailand (21), contributed important studies. Other countries such as Iran (42), Qatar (43), and Israel (44) provided evidence from arid or hot environments. However, Latin America, sub-Saharan Africa, and parts of Southeast Asia remain significantly underrepresented, suggesting a regional imbalance in the current literature.

Risk of bias assessment among the randomized crossover trials

The risk of bias assessment across the randomized crossover trials demonstrated a generally low risk of bias across most methodological domains (table 1). All 41 studies (100%) were rated low risk in three key areas: randomization process, deviations from intended interventions (for both assignment and adherence effects), and missing outcome data, suggesting that the majority of trials had a robust design, maintained protocol adherence, and achieved high data completeness.

In the domain of bias due to deviations from intended intervention, only one study (2.44%) was rated as having some concern when analyzed for the effect of adherence to intervention, indicating a minor deviation in participant behavior or compliance that may have influenced

outcomes. Similarly, bias in the measurement of outcomes was uniformly low across all studies.

However, a notable concern emerged in the domain of selection of the reported result, where 15 out of 41 studies (36.59%) were judged to be at high risk, and an additional 19 studies (46.34%) were rated as having some concerns with respect to reporting the outcome parameters. This suggests that selective outcome reporting or incomplete pre-specification of analysis plans may have affected the transparency and reliability of the reported findings in a significant portion of studies.

Overall, while the methodological quality of the crossover trials was strong in terms of study design, adherence, and data integrity, the predominant limitation lies in the potential for reporting bias, which may affect the interpretation of efficacy outcomes. Consequently, although most studies were assessed as having low overall risk, the high frequency of concerns in reporting domains should be considered when drawing conclusions from the evidence.

Risk of bias assessment among RCT parallel studies

All 4 included studies carried a low risk of bias among all the domains assessed (table 2).

Risk of bias assessment among the non-randomized intervention trials

The risk of bias assessment revealed notable methodological concerns across several domains among the included non-randomized studies (table 3). The most prominent issue among the included 24 non-randomized interventional trial was a serious risk of bias due to confounding, which was observed in the majority of studies. Specifically, 70.83% of the studies under Variant A and 95.83% under Variant B were judged to have a serious risk in this domain, indicating limited adjustment for baseline differences or other confounding variables. Similarly, classification of interventions posed serious – some concerns, with 25% of studies, likely due to inadequate clarity or consistency in identifying and categorizing intervention exposure. In contrast, the

Table 2. Risk of bias assessment for randomized controlled trials (RCT) – parallel studies.

Studies	Randomization process in a cluster-randomized trial	Timing of identification or recruitment of participants in a cluster-randomized trial	Deviations from intended intervention in a cluster RCT (effect of assignment to intervention)	Deviations from the intended interventions (effect of adhering to the assigned intervention)	Missing data in a cluster-randomized trial	Outcome measurement in a cluster RCT (signaling questions)	Selection of the reported result in a cluster RCT (signaling questions)	Overall study-wise prediction
Chicas et al, 2021 (22)	Low	Low	Low	Low	Low	Low	Low	Low
Tay et al, 2020 (46)	Low	Low	Low	Low	Low	Low	Low	Low
Colburn et al, 2011 (33)	Low	Low	Low	Low	Low	Low	Low	Low
Shojaei et al, 2025 (70)	Low	Low	Low	Low	Low	Low	Low	Low

Table 3. Risk of bias assessment for non-randomized intervention studies.

Studies	Confounding		Classification of interventions	Participant selection (study or analysis)	Deviations from intended interventions		Missing data	Outcome measurement	Selection of the reported result	Overall study-wise prediction
	Variant - A	Variant - B			Variant - A	Variant - B				
Ashtekar et al, 2019) (39)	Low	Serious	Low	Low	Low	Low	Low	Moderate	Low	Serious
Zhao et al, 2018) (26)	Low	Serious	Low	Low	Low	Low	Low	Moderate	Low	Serious
Chan et al, 2017) (30)	Low	Serious	Low	Low	Low	Low	Low	Low	Low	Serious
Ashtekar et al, 2016) (45)	Serious	Serious	Low	Low	Low	Low	Low	Low	Low	Serious
Bartkowiak et al, 2017) (71)	Serious	Serious	Low	Low	Moderate	Low	Low	Low	Low	Serious
Glitz et al, 2015 (35)	Serious	Serious	Low	Low	Low	Low	Low	Low	Low	Serious
Jovanovi et al, 2014 (73)	Serious	Serious	Low	Low	Low	Low	Low	Low	Low	Serious
Wickwire et al, 2009 (63)	Serious	Serious	Serious	Low	Low	Low	Low	Low	Low	Serious
Barwood et al, 2009 (48)	Serious	Serious	Low	Low	Low	Low	Low	Low	Low	Serious
Hadid et al, 2008 (44)	Serious	Serious	Low	Low	Low	Low	Low	Low	Low	Serious
Cadarette et al, 2007 (53)	Serious	Serious	Serious	Low	Low	Low	Low	Low	Low	Serious
Cadarette et al, 2006 (51)	Low	Moderate	Low	Low	Low	Low	Low	Serious	Low	Serious
McLellan et al, 2004 (74)	Serious	Serious	Low	Low	Low	Low	Low	Low	Low	Serious
Cadarette et al, 2003 (52)	Serious	Serious	Low	Low	Low	Low	Low	Low	Low	Serious
Constable et al, 1994 (56)	Serious	Serious	Low	Low	Low	Low	Low	Low	Low	Serious
Holmr et al, 1992 (58)	Serious	Serious	Low	Low	Low	Low	Low	Low	Low	Serious
Bishop et al, 1991 (49)	Serious	Serious	Low	Low	Low	Low	Low	Low	Low	Serious
Van et al, 1972 (88)	Serious	Serious	Low	Low	Low	Low	Low	Low	Low	Serious
Soleimani et al, 2023 (42)	Serious	Serious	Low	Low	Low	Low	Low	Low	Low	Serious
Tokizawa et al, 2020 (37)	Low	Serious	Low	Low	Low	Low	Low	Low	Low	Serious
Willmott et al, 2018 (36)	Low	Serious	Moderate	Low	Low	Low	Moderate	Low	Low	Serious
Parameswarappa et al, 2017 (41)	Serious	Serious	Moderate	Low	Low	Low	Moderate	Low	Low	Serious
Nag et al, 1998 (40)	Serious	Serious	Moderate	Low	Low	Low	Low	Low	Low	Serious
Jamshidi et al, 2025 (67)	Low	Serious	Serious	Low	Low	Low	Moderate	Low	Low	Serious

selection of participants into the study or analysis was generally not a major source of bias, with most studies judged to have a low risk in this domain, and only a small proportion showing moderate or serious concerns.

Encouragingly, bias due to deviations from intended interventions, missing data, and outcome measurement was consistently rated as low in nearly all studies, suggesting good adherence to intervention protocols, completeness of collecting post-intervention data, and objective measurement procedures. The risk of bias due to selective reporting of results was also low in the majority of studies, with only a few rated as moderate or serious. Taken together, these findings indicate that while most studies were methodologically sound in terms of conduct and reporting, the overall credibility of the evidence base is compromised by the persistent and widespread risk of confounding and ambiguity in intervention classification. As a result, the overall risk of bias was judged to be serious for the majority of studies, warranting cautious interpretation of the findings and conclusions drawn from the synthesis, including the network meta-analysis.

Certainty of evidence

Based on the GRADE evaluation, the overall certainty of evidence regarding the impact of wearable cooling interventions on physiological and perceptual outcomes under heat strain conditions was judged to be low to very low. A comprehensive evidence profile along with

the summary of findings is provided in supplementary table 3. The downgraded certainty largely reflects substantial risks of bias, potential publication bias, and other methodological limitations identified through the risk of bias assessment and contour-enhanced funnel plot analyses. Furthermore, the reliability of the evidence was weakened by small mean differences coupled with wide 95% confidence intervals (CI), indicating variability and imprecision across the studies. Taken together, these limitations highlight the pressing need for more rigorous, high-quality research.

Core body temperature

All but six studies (26, 30, 39, 41, 45, 46) reported measurements of core body temperature. However, due to the absence of both central tendency and dispersion values, as well as results presented only in graphical form, data from 36 studies were available for analysis (9, 10, 24, 27–29, 33–35, 38, 43, 44, 47–70).

Except for Ciuha 2023—which reported both rectal and gastrointestinal (GI) temperatures—all studies measured either rectal (N=20) or GI temperature (N=14) or tympanic membrane (N=3) (9). Several studies [eg, (9, 24, 49)] evaluated more than one intervention type; each intervention arm was treated as a separate observation in the analysis. In some studies, no statistically significant change in core body temperature was observed between cooling intervention and control groups (10, 33, 43, 50, 53, 55, 57, 59, 66).

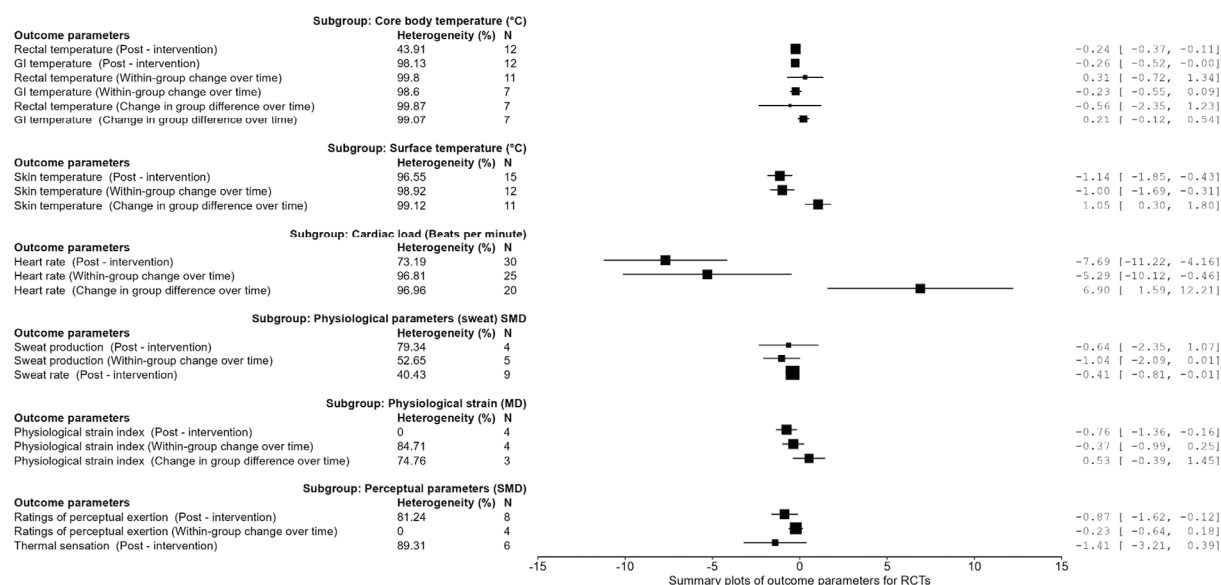


Figure 2. Summary forest plots of all outcome parameters (RCT).

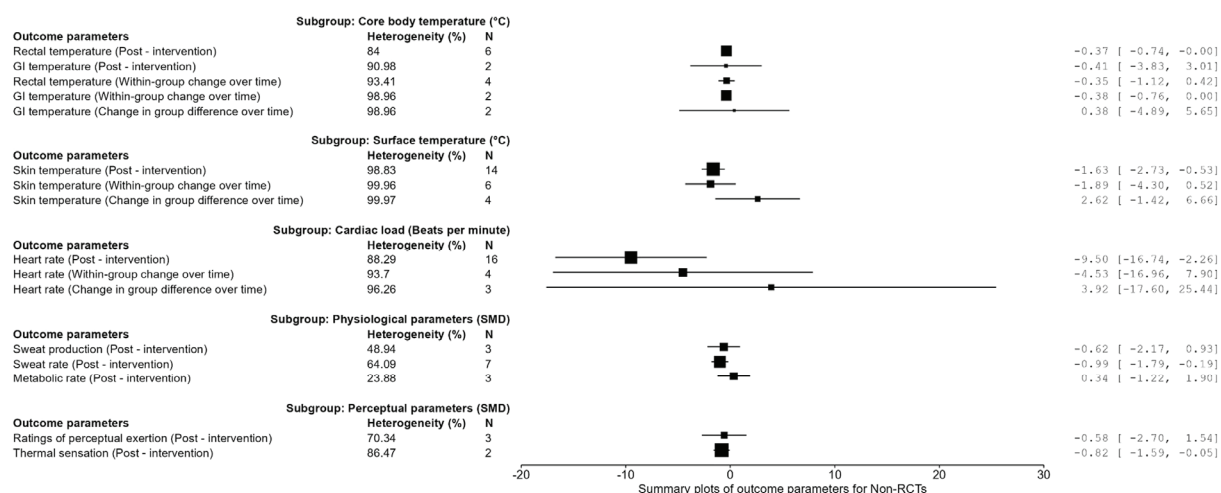


Figure 3. Summary forest plots of all outcome parameters (non-RCT).

Post intervention comparison

Eighteen (rectal) and fourteen (GI) and three (tympanic), studies measured immediately after heat exposure. Compared with controls, cooling interventions reduced rectal temperature by -0.24°C (95% CI -0.37 – -0.10 ; $I^2=43.91\%$; $N=12$) in RCT and -0.37°C (95% CI -0.92 – -0.18 ; $I^2=84\%$; $N=6$) for non-RCT (figures 2 and 3 and supplementary figure 1). GI temperature in RCT showed a pooled reduction of -0.26°C (95% CI -0.52 – -0.001 ; $I^2=98.13\%$; $N=12$) and -0.41°C (95% CI -3.83 – 3.01 ; $I^2=90.98\%$; $N=2$) for non-RCT (figure 2 and 3 and supplementary figure 2). For tympanic temperature, the

pooled differences were -0.19°C (95% CI -1.49 – 1.11 ; $I^2=87.58$; $N=3$) (figure 4). Subgroup analyses by intervention type were inconclusive (supplementary tables 4 and 5). Egger's tests showed no significant funnel-plot asymmetry for rectal ($P=0.686$ RCT; $P=0.962$ non-RCT) or GI ($P=0.99$ RCT) or tympanic ($P=0.82$) temperature (supplementary figures 3 and 4).

Within-group (difference of difference) comparison

Fifteen (rectal), nine (GI) and three (tympanic), observations provided pre–post differences between intervention and control. For rectal temperature the pooled mean dif-

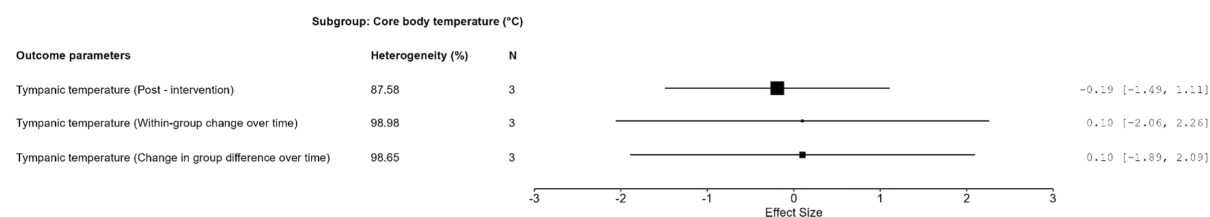


Figure 4. Summary forest plots of all outcome parameters (combined randomized controlled trials (RCT) and non-RCT).

ferences were 0.31 °C (95% CI -0.72–1.35; $I^2=99.86\%$; $N=11$) for RCT and -0.35 °C (95% CI -1.12–0.43; $I^2=93.41\%$; $N=4$) for non-RCT, indicating no significant effect (figures 2 and 3 and supplementary figure 5). For GI temperature the pooled differences were -0.23 °C (95% CI -0.55–0.1; $I^2=98.6\%$; $N=7$) for RCT and -0.38 (-5.66–4.89; $I^2=98.96\%$; $N=2$) for non-RCT, also non-significant (figures 2 and 3 and supplementary figure 6). For tympanic temperature the pooled differences were 0.1 °C (95% CI -2.06–2.26; $I^2=98.98$; $N=3$) (figure 4). Subgroup analyses were inconclusive (supplementary tables 6 and 7). Egger's tests did not show substantial asymmetry for rectal ($P=0.45$ RCT; $P=0.24$ non-RCT) or GI ($P=0.23$ RCT) measures (supplementary figure 7).

Change in between-group differences over time

Seven rectal, nine GI and three tympanic observations reported change in between-group differences. For rectal temperature pooled estimates were -0.56 °C (95% CI -2.35–1.24; $I^2=99.87\%$; $N=7$) for RCT compared with controls (figure 2 and supplementary figure 8). GI pooled estimates were 0.21 °C (95% CI -0.12–0.54; $I^2=99.07\%$; $N=7$) for RCT and 0.38 (95% CI -4.89–5.66; $I^2=98.96\%$; $N=2$) and non-RCT; none reached statistical significance (figures 2 and 3 and supplementary figure 9). For tympanic temperature, the pooled differences were 0.1 °C (95% CI -1.89–2.1; $I^2=98.65$; $N=3$) (figure 4). Subgroup analyses were inconclusive (supplementary tables 8 and 9), and Egger's tests showed no evidence of funnel-plot asymmetry for rectal ($P=0.69$) or GI ($P=0.19$) or tympanic ($P=0.75$) measures.

Skin temperature

A total of 47 included studies measured surface (skin) temperature (10, 11, 20, 24, 25, 27–29, 31, 32, 34–40, 42–45, 47–51, 53–55, 58–66, 68–76). Due to the absence of both central tendency and dispersion values, and in some cases results being reported only in graphical form, only 27 studies were eligible for quantitative synthesis. Notably (29, 31, 40, 43, 49, 53, 55, 66), did not observe statistically significant differences in skin temperature between cooling interventions and control conditions.

Post intervention comparison

Across 29 observations, cooling interventions significantly lowered skin temperature to -1.14°C (95% CI -1.85– -0.42; $I^2=96.55\%$; $N=15$) for RCT and -1.63°C (95% -2.73– -0.52; $I^2=98.83\%$; $N=14$) for non-RCT (figures 2 and 3 and supplementary figure 10). Subgroup analyses suggested water/ice and PCM interventions were effective but with high heterogeneity (supplementary table 10). Egger's tests indicated funnel plot asymmetry ($P=0.008$ RCT; $P=0.022$ non-RCT), suggesting possible publication bias (supplementary figure 11).

Within-group (difference of difference) comparison

Eighteen observations were available, and pooling them showed mean reductions of -1 °C (95% CI -1.69– -0.31; $I^2=98.92\%$; $N=12$) for RCT and -1.89°C (95% CI -4.31–0.52; $I^2=99.96\%$; $N=6$) for non-RCT compared with controls (figure 2 and 3 and supplementary figure 12). Subgroup analyses were inconclusive (supplementary table 11). Egger's tests showed no evidence of publication bias ($P=0.965$ RCT; $P=0.155$ non-RCT) (supplementary figure 13).

Change in between-group differences over time

Pooled reduction from 15 available observations was 1.05°C (95% CI 0.3–1.8; $I^2=99.12\%$; $N=11$) for RCT and 2.62°C (95% CI -1.42–6.67; $I^2=99.97\%$; $N=4$) for non-RCT (figures 2 and 3 and supplementary figure 14). Subgroup analyses were inconclusive (supplementary table 12). Egger's tests indicated no bias in RCT ($P=0.961$) but possible asymmetry in non-RCT ($P=0.143$) (supplementary figure 15).

Heart rate

All included studies except Udayraj et al (25) and Nag et al (40) measured heart rate. Several studies, including (8, 21, 24, 29, 31, 32, 35, 36, 43–46, 51–53, 55, 61, 65, 72, 73, 76–78) reported no statistically significant difference in the average heart rate between cooling interventions and controls. Due to the unavailability

of both central tendency and dispersion values in some studies, or results reported only graphically, data from 41 studies were eligible for quantitative analysis (9, 11, 23, 24, 27, 29, 33–35, 37–39, 42, 44–49, 51–53, 55–65, 73, 78, 79).

Post intervention comparison

Forty-six observations showed that cooling interventions significantly lowered heart rate compared with controls: -7.69 beats per minute (95% CI -11.22– -4.15; $I^2=73.19\%$; $N=30$) in RCT and -9.5 bpm (95% CI -16.75– -2.26; $I^2=88.29\%$; $N=16$) in non-RCT (figures 2 and 3 and supplementary figure 16). Subgroup analysis suggested water/ice and PCM-based cooling were beneficial, though heterogeneity was high (supplementary table 13). Egger's test ($P=0.055$ for RCT; $P=0.224$ for non-RCT) showed possible publication bias (supplementary figure 17).

Within-group (difference of difference) comparison

Twenty-nine observations indicated significantly lower pooled mean heart rate in intervention groups: -5.29 bpm (95% CI -10.13– -0.46; $I^2=96.81\%$; $N=25$) for RCT and -4.53 bpm (95% CI -16.96–7.91; $I^2=93.7\%$; $N=4$) for non-RCT (figures 2 and 3 and supplementary figure 18). Subgroup results were inconclusive (supplementary table 14). Egger's test ($P=0.183$ for RCT; $P=0.461$ for non-RCT) suggested low risk of publication bias (supplementary figure 19).

Change in between-group differences over time

Twenty-three observations showed pooled mean differences of 6.9 bpm (95% CI 1.59–12.22 $I^2=96.96\%$; $N=20$) for RCT and 3.92 bpm (95% CI -17.6–25.44 $I^2=96.26\%$; $N=3$) for non-RCT (figures 2 and 3 and supplementary figure 20). Subgroup analysis was inconclusive (supplementary table 15). Egger's test ($P=0.72$ for RCT; $P=0.001$ for non-RCT) suggested low risk of bias (supplementary figure 21).

Sweat production

A total of 14 included studies reported sweat production (25, 32, 35, 45, 47, 48, 54, 71, 72, 78–80). Notably, Barwood et al. (2009) and Inoue et al. (2023) did not observe statistically significant differences between intervention and control groups (48, 78). Due to the absence of central tendency and dispersion values and/or results being available only in graphical form, data from 11 studies were eligible for quantitative synthesis.

Post intervention comparison

Seven observations on sweat production, reported in varied units, were pooled using standardized mean difference (SMD). Cooling interventions showed no significant effect -0.64 (95% CI -2.35–1.07; $I^2=79.34\%$; $N=4$) for RCT and -0.62 (95% CI -2.17–0.94; $I^2=48.94\%$; $N=3$) for non-RCT, indicating no statistically significant effect (figures 2 and 3 and supplementary figure 22). Subgroup results were inconclusive (supplementary table 16). Egger's test ($P=0.95$ for RCT; $P=0.68$) suggested low risk of publication bias.

Within-group (difference of difference) comparison

Five observations reported a pooled SMD of -1.04 units (95% CI -2.09–0.01; $I^2=52.65\%$; $N=5$) for RCT, indicating a significant reduction in intervention groups versus controls (figure 2 and supplementary figure 23). Subgroup findings were inconclusive (supplementary table 17). Egger's test ($P=0.407$) showed no funnel plot asymmetry, suggesting low risk of bias.

Sweat rate

A total of 26 included studies reported sweat rate (11, 20, 23, 28, 29, 31–34, 37, 44, 49, 51–53, 55, 56, 58, 60, 63, 65, 73, 74, 76, 81). Notably, several studies (11, 24, 44, 54, 65, 77) reported no statistically significant differences between intervention and control groups. Due to the unavailability of both central tendency and dispersion values and/or results presented only in graphical form, data from 16 studies were eligible for meta-analysis.

Post intervention comparison

Sixteen studies assessed sweat rate post-heat stress or rest. Due to varied reporting units, results were expressed as SMD. Cooling interventions significantly reduced sweat rate: -0.41 (95% CI -0.82– -0.01; $I^2=40.43\%$; $N=9$) for RCT and -0.99 (95% CI -1.79– -0.19; $I^2=64.09\%$; $N=7$) for non-RCT (figures 2 and 3 and supplementary figure 24). Subgroup analysis indicated water/ice-based interventions were particularly effective (supplementary table 18). Egger's test ($P=0.117$ for RCT; $P=0.222$ for non-RCT) showed no evidence of publication bias (supplementary figure 25).

Metabolic rate

Four included studies reported metabolic rate (35, 43, 52, 53). Notably, Glitz et al (35) did not observe significant differences between intervention and control groups.

All four studies measured metabolic rate either immediately after heat stress exposure or following a rest phase. The pooled SMD between groups was 0.34 (95% CI -1.22–1.9; $I^2=23.88\%$; $N=3$) for non-RCT, indicating no statistically significant difference (figure 3 and supplementary figure 26). Egger's test ($P=0.11$) suggest a low risk of publication bias. Due to the small number of studies, publication bias could not be formally assessed.

Ratings of perceptual exertion

Twenty included studies assessed ratings of perceptual exertion (RPE) (11, 26, 30, 31, 34, 38, 44, 47, 48, 50, 57, 59, 60, 64, 69, 72, 76, 77, 79, 80). Several (11, 44, 48, 57, 72, 76, 77, 80) reported no statistically significant group differences. Due to the lack of both central tendency and dispersion measures and/or results presented only in graphical form, twelve studies were eligible for meta-analysis.

Post intervention comparison

Eleven studies reported RPE post-heat stress or rest. Cooling interventions significantly reduced RPE with pooled SMD -0.87 (95% CI -1.62– -0.11; $I^2=81.24\%$; $N=8$) for RCT and -0.58 (95% CI -2.7–1.55; $I^2=70.34\%$; $N=3$) for non-RCT (figures 2 and 3 and supplementary figure 27). Subgroup analysis was inconclusive (supplementary table 19). Egger's test ($P=0.392$ for RCT; $P=0.606$ for non-RCT) suggested low risk of publication bias (supplementary figure 28).

Within-group (difference of difference) comparison

Four observations showed pooled SMD -0.23 (95% CI -0.64–0.18; $I^2 = 0\%$; $N=4$) for RCT, indicating no significant effect (figure 2 & supplementary figure 29). Subgroup analysis was inconclusive (supplementary table 20), and Egger's test ($P=0.825$) indicated low risk of bias.

Change in between-group differences over time

Three observations showed pooled SMD 4.5 (95% CI -5.25– 14.26 $I^2 = 95.18\%$; $N=3$) (figure 2 & supplementary figure 30). Subgroup analysis was inconclusive (supplementary table 21). Egger's test ($P=0.001$) suggested low risk of bias.

Thermal sensation

Twenty-four studies reported thermal sensation scores (10, 11, 26, 30, 31, 34, 38, 44, 47, 48, 50, 57, 59, 60, 64, 67–69, 72, 76, 77, 79, 80, 82). Several studies (11,

44, 48, 57, 72, 76, 77, 80) did not observe significant group differences. Due to the absence of complete central tendency and dispersion measures and/or reliance on graphical data, only eight studies were eligible for meta-analysis.

Post intervention comparison

Across these eight studies, cooling interventions were associated with a pooled SMD of -1.41 (95% CI -3.21–0.4; $I^2 = 89.31\%$; $N=6$) for RCT and -0.82 (95% CI -1.59– -0.05; $I^2=86.47\%$; $N=2$) for non RCT, compared with controls, indicating a statistically significant improvement in thermal sensation (figures 2 and 3 and supplementary figure 31). The leave-one-out residual heterogeneity test did not identify any potential outliers. Subgroup analysis based on the type of wearable cooling intervention was inconclusive (supplementary table 22). Egger's test ($P=0.132$ for RCT) suggesting a low risk of publication bias.

Physiological strain

Eleven included studies assessed physiological strain using the Physiological Strain Index (PSI) (10, 11, 28, 30, 44, 51–53, 55, 57, 64). Several studies (10, 52, 53) reported no statistically significant group differences. Due to the lack of both central tendency and dispersion measures and/or results presented only in graphical form, seven studies were eligible for meta-analysis. All these studies estimated PSI using method described by Moran et al (83).

Post intervention comparison

Six studies reported PSI post-heat stress or rest. Cooling interventions reduced PSI with pooled MD -0.76 (95% CI -1.36– -0.16; $I^2 = 0\%$; $N=4$) for RCT and -2.4 (95% CI -35.43–30.63; $I^2=96.77\%$; $N=2$) for non-RCT (figures 2 and 3 and supplementary figure 32). Subgroup analysis was inconclusive (supplementary table 23). Egger's test ($P=0.948$ for RCT) suggested low risk of publication bias.

Within-group (difference of difference) comparison

Four observations showed pooled MD -0.37 (95% CI -0.99–0.26; $I^2=84.71\%$; $N=4$) for RCT, indicating no significant effect (figure 2 and supplementary figure 33). Subgroup analysis was inconclusive (supplementary table 24), and Egger's test ($P=0.08$) indicated low risk of bias.

Change in between-group differences over time

Three observations showed pooled MD 0.53 (95% CI -0.4–1.45 $I^2 = 74.76\%$; $N=3$) for RCT (figure 2 and supplementary figure 34). Subgroup analysis was inconclusive (supplementary table 25). Egger's test ($P=0.797$) suggested low risk of bias.

Discussion

The present systematic review broadly aimed at evaluating the effectiveness of various wearable cooling interventions in reducing the heat strain. The findings collectively indicate that wearable cooling strategies exert meaningful physiological relief by attenuating heat storage and cardiovascular strain during heat exposure. Compared with controls, they were associated with significant reductions in rectal ($-0.24\text{ }^{\circ}\text{C}$) and gastrointestinal temperatures ($-0.17\text{ }^{\circ}\text{C}$) immediately after exposure in RCT, though these effects were less evident in over-time analyses and non-RCT, likely reflecting small samples and high heterogeneity. Skin temperature was robustly reduced ($-1.02\text{ }^{\circ}\text{C}$), and heart rate decreased both post-exposure (-7 bpm). More pronounced and consistent benefits were observed for peripheral and cardiovascular indicators, including skin temperature and heart rate, suggesting that cooling interventions primarily influence heat dissipation at the body surface and circulatory load rather than deeply altering core thermoregulation. Importantly, perceptual outcomes supported these findings, with improved thermal sensation reported following cooling. Despite the overall positive effects, heterogeneity was high across nearly all outcomes, and publication bias was detected for majority of measures.

Across studies, cooling strategies consistently influenced outcomes that are most sensitive to external heat exchange—namely skin temperature, heart rate, and sweat rate—while effects on core temperature, metabolic rate, and total sweat production were more variable. However, the scarcity of available literature prevents from direct comparison of the effectiveness of different wearable cooling interventions, making head-to-head evaluation challenging. Both water/ice and PCM-based cooling interventions consistently produced significant reductions in surface temperature, heart rate, and sweat rate compared with no intervention at the end of heat stress trials. However, as standalone strategies either of these cooling strategies failed to demonstrate consistent effects across physiological outcomes.

Wearable cooling interventions function primarily through distincy but complimentary thermoregulatory mechanisms including conductive cooling and enhanced heat dissipation. In conductive cooling, body heat is

transferred to the cooling medium (eg, water, ice, or PCM) until thermal equilibrium is achieved. Water/ice vests provide rapid cooling through direct heat absorption, whereas PCM-based vests maintain cooling at a more stable temperature because the PCM absorbs latent heat during its phase transition at a higher temperature threshold than water, thereby offering sustained comfort (84). In contrast, ventilator or evaporative fabrics facilitate heat dissipation by accelerating sweat evaporation, allowing faster clearance of moisture and improved convective cooling for the wearer.

Previous systematic reviews on wearable cooling have been constrained by limited scope, involving only outdoor workers and not including meta-analyses for quantitative comparisons of different interventions (85, 86). The present review is among the earliest to quantify and report pooled estimates of the effects of wearable cooling interventions across multiple outcomes. Further, the present review extends existing evidence by clarifying where cooling interventions are most consistently effective and where benefits are more context-dependent.

Importantly, while significant benefits were observed for several physiological and perceptual endpoints, the analysis was challenged by high heterogeneity, risk of bias in a subset of studies, resulting in low-to-very-low certainty of evidence. Heterogeneous and inconsistently reported heat stress metrics because of scarce integration of standardized indices such as wet bulb globe temperature, universal thermal climate, or predicted heat strain, limited the normalization of effects to exposure severity and constrains translation to occupational guidelines. Given known sex, and age-related differences in thermoregulation, sweat response, and cardiovascular strain, and limited representation of women and older workers, the findings primarily reflect responses among young, healthy men and may not be generalizable to women. Although several outcomes showed statistically significant improvements, modest effect sizes, particularly for core temperature, should be interpreted as context-dependent physiological mitigation rather than universal protection against heat-related risk. Overall, these findings indicate that wearable cooling interventions can effectively attenuate heat strain and enhance thermal comfort, but the magnitude and consistency of benefits vary across intervention types and outcomes. The evidence base remains limited, underscoring the need for well-designed, rigorously conducted, adequately powered trials with standardized outcome reporting to refine comparative effectiveness, address heterogeneity, and guide practical implementation for diverse occupational settings.

With the growing impact of climate change, occupational heat strain is increasingly recognized as a significant public health and workplace hazard. Workers

exposed to high ambient temperatures face heightened risks of heat-related illnesses, reduced productivity, and long-term health consequences. This climate-related vulnerability is most pronounced among workers in LMIC and informal sectors, where limited engineering controls, social protection, and healthcare access exacerbate risks. The present findings provide robust evidence supporting the role of wearable cooling interventions in attenuating physiological strain and improving thermal comfort. The wearable cooling interventions are practical risk-reduction tools that can complement administrative and engineering controls, especially in settings where environmental modification is not feasible. By demonstrating measurable benefits across multiple outcomes, these results strengthen the certainty around their effectiveness. Accordingly, wearable cooling measures can be recommended as effective interventions for mitigating the adverse effects of occupational heat strain.

Beyond their immediate benefits, present observation highlights the importance of integrating cooling interventions within broader occupational health frameworks and policy-relevant climate adaptation strategies. Adoption of such interventions can contribute not only to worker safety but also to sustaining productivity under rising global temperatures. Future research should continue to refine these approaches, ensuring cost-effectiveness, accessibility, and scalability across diverse workplace environments, particularly for informal and resource-limited sectors in LMIC where vulnerability to climate-driven heat stress is greatest.

Concluding remarks

The observations from current systematic review demonstrate climate related vulnerability of the worker, and consistent physiological and perceptual benefits of wearable cooling interventions particularly in RCT. However, the effects varied across intervention types; water/ice and PCM-based interventions were more effective for lowering surface temperature and cardiovascular strain, whereas ventilator/evaporative cooling showed variable outcomes. Despite these benefits, high heterogeneity, potential publication bias, and overall low certainty of evidence highlight the need for more robust and standardized trials. In light of the increasing risks posed by climate change, integrating wearable cooling interventions into occupational health strategies can improve worker safety, comfort, and productivity. Future research should focus on head-to-head comparisons, scalability, and cost-effectiveness to guide their practical application across diverse workplace settings.

Funding

ICMR investigator-initiated research proposals grant-2023-0000186/ENV/GY/2023

Declaration of interests

All authors declare no conflict of interest

Data sharing

All data used in this study are sourced from existing primary literature; the collected data will be shared on reasonable request.

Acknowledgement

All authors acknowledge the contributions of the primary study authors whose work was included in this systematic review, as well as the scientific review committee and ICMR experts for their valuable feedback during the conception of this proposal.

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Received for publication: 6 October 2025