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THE RIVISTA ITALIANA DI ERGONOMIA, *of the* S.I.E. - *Italian Society of Ergonomics, is a scientific journal that operates nationally and internationally for the promotion and development of ergonomics and the study of human factors, and the dissemination and systematization of knowledge and experiences related to the ergonomic approach, in close relationship with the social, environmental and productive realities where human beings, operate and live, coherently with the goals of the* SIE.

Supported by an international scientific committee and using a double-blind reviewing process, the journal publishes original contributions from research and applications on ergonomic issues, in its various aspects and related to the different contexts and human activities.

The RIVISTA ITALIANA DI ERGONOMIA *is aimed at ergonomic professionals and all those interested in applying the principles and methods of ergonomics / human factors in the design, planning and management of technical and social systems, in work or in leisure.*

INDEX

Designing the future of workwear. Smart solutions for thermal safety in the climate change era

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Keywords: climate change, workers, safety, health, wearable technology, smart clothing

Abstract

In contemporary times, the rise in the Earth's surface temperature has been largely attributed to anthropogenic causes. The increasing intensity of extreme weather events and prolonged heat waves has significantly impacted work and production activities, leading to widespread thermal discomfort and elevated heat stress. Construction and road workers are particularly exposed to health and occupational safety issues in this context, as they face heightened workplace risks and an increased risk of developing short- and long-term occupational diseases. A study of existing literature reveals that personal protective equipment designed for thermal mitigation remains underutilised, largely due to ergonomic limitations, high production costs, inadequate integration into daily workflows, and cultural resistance. In response, wearable technologies have emerged as a promising avenue for counteracting heat-related

risks. Thermoregulation systems that can detect, respond to and adapt to thermal stimuli show significant potential for protecting the most exposed workers. This paper provides a synthesis of existing wearable thermoregulation systems, identifies key gaps in their ergonomic implementation, and outlines future directions for interdisciplinary research and design innovation.

Introduction

Since the earliest stages of human history, individuals have been exposed to environmental and physiological risks associated with occupational activities. Notably, as early as the Roman era, Pliny the Elder documented the implementation of rudimentary preventive measures by craftsmen working with cinnabar: a mineral employed to produce a distinctive red pigment. «Persons polishing cinnabar in workshops tie on their face loose masks of bladder-skin, to prevent their inhaling the dust in breathing, which is very pernicious, and nevertheless to allow them to see over the bladders» (Pliny the Elder, ca. 77–79 C.E., p. 95, trans. by Rackham). In the 17th century, Bernardino Ramazzini, considered the father of occupational medicine, asserted the correlation between occupational exposures and the onset of specific diseases in his work *De Morbis Artificum Diatriba* (1700) (Spaterna, 2022), thereby anticipating the modern concept of 'cumulative trauma disorders' (Franco & Franco, 2001). Subsequently, inspection reports from the Industrial Revolution documented frequent episodes of heat collapse and impaired vigilance—phenomena now recognised as early indicators of 'occupational heat stress' (Ogden, 2023). These historical accounts establish a clear thread linking past occupational hazards to contemporary challenges posed by Climate Change (CC). Global warming, accelerated by anthropogenic CC, is leading to an increase in the frequency and intensity of heatwaves, with direct consequences for public health and worker safety (ILO, 2024). This highlights the need to address 'old' risks from new ergonomic and preventive perspectives. According to current climate projections (IPCC, 2023), continued greenhouse gas emissions are likely to push global warming beyond the 1.5°C threshold in the near future. Furthermore, it is estimated that the highest summer temperatures recorded between 1950 and 1979 will occur at least 70% of the time between 2035 and 2064 (NCA, 2014). In the coming decades, this will increase the incidence of heat-related illnesses, poor air and water quality, declining food resources, and a subsequent decrease in labor productivity (ISS, 2009).

Considering these premises, it is clear that the risk of heat exposure for humans will become increasingly critical shortly. This concern is especially pertinent for outdoor workers, such as those in the agricultural and construction sectors. Accordingly, this paper concentrates on the occupational hazards posed by heat waves. The study begins with an analysis of the literature and explores the consequences of prolonged heat exposure in work environments. Focus is directed toward emerging advancements in monitoring physiological parameters and preventing heat stress through wearable technologies. Finally, the paper offers a discussion on potential interdisciplinary approaches to effectively address these emerging challenges.

Methodology

This contribution is structured along two main thematic lines: (i) the correlation between CC and its impacts on human health; (ii) the evolution of prevention strategies, with particular attention to regulatory frameworks and wearable technologies for monitoring heat stress. The aim is to offer an updated synthesis of recent scientific and institutional contributions, in order to recontextualise historically known occupational risks in light of contemporary environmental, technological, and social transformations. Sources were selected through consultation of scientific databases and institutional websites, including those of the World Health Organization (WHO), the National Institute for Insurance against Workplace Accidents (INAIL), and the European Agency for Safety and Health at Work (EU-OSHA). Although the study is not structured as a systematic review, it adopts a qualitative, narrative synthesis approach, prioritising sources based on their relevance, recency, and representativeness in the international debate. The literature search was guided by keywords such as 'climate change', 'heat stress', ‘human health', 'wearable technologies', and 'smart garments'. Alongside technical and scientific data, the paper also integrates historical and cultural insights—for instance, traditional adaptation strategies of desert nomadic populations—which exemplify embodied resilience in extreme environments. In the following sections, we explore the physiological, occupational, and regulatory dimensions of heat stress, beginning with a general overview of climate-health interactions.

Living and working in extremes

Global surface temperatures have risen by approximately 1°C above pre-industrial levels (IPCC, 2023), with 0.8°C of this increase occurring since the 1970s (NASA Earth Observatory, n.d.). Although data remain somewhat fragmented and geographically heterogeneous, evidence from the past two decades confirms that health risks arise from the interaction between climate-related hazards (both acute events and long-term trends) and the vulnerability and exposure of human and natural systems (IPCC, 2014). The primary pathways through which CC affects health are: i) direct impacts, such as exposure to high temperatures, storms, floods and air pollution; ii) effects mediated by natural systems, such as vector-borne diseases (e.g. malaria, dengue fever and Lyme disease); iii) indirect impacts, such as food security and water scarcity (WHO, 2021; FAO, 2016). These pathways reveal a systemic cascade wherein CC and health risks are interlinked, with each effect potentially amplifying or triggering others (Haines et al., 2019; Campbell-Lendrum et al, 2023). A significant study estimates that anthropogenic CC accounts for approximately 37.0% (range: 20.5% to 76.3%) of heat-related deaths during the warm season (Vicedo-Cabrera et al., 2021). The WHO has identified climate change (CC) mitigation and the management of its health impacts as priority actions within the Global Public Health Agenda (WHO, 2021). Exposure to extreme heat for a prolonged time, without the ability to dissipate it effectively, can trigger a chain reaction of physiological dysfunctions across multiple organ systems (McKeever, 2021). Figure 1 outlines the multifactorial pathways through which CC impacts human health, with particular emphasis on thermal stress resulting from both extreme heat and cold. CC is shown as a central driver that increases the frequency and severity of both heat waves and cold spells. These exposures lead to direct health effects—such as heatstroke, dehydration, cardiovascular and respiratory complications—as well as indirect effects, including reduced labor productivity, increased healthcare demand, and socio-economic vulnerabilities. Particularly at risk are outdoor workers, the elderly, children, and individuals with pre-existing health conditions (Acharya et al., 2018; Commissione Europea, n.d.). This paper focuses on the impact of extreme heat on outdoor workers and the potential of wearable technologies to increase thermal comfort.

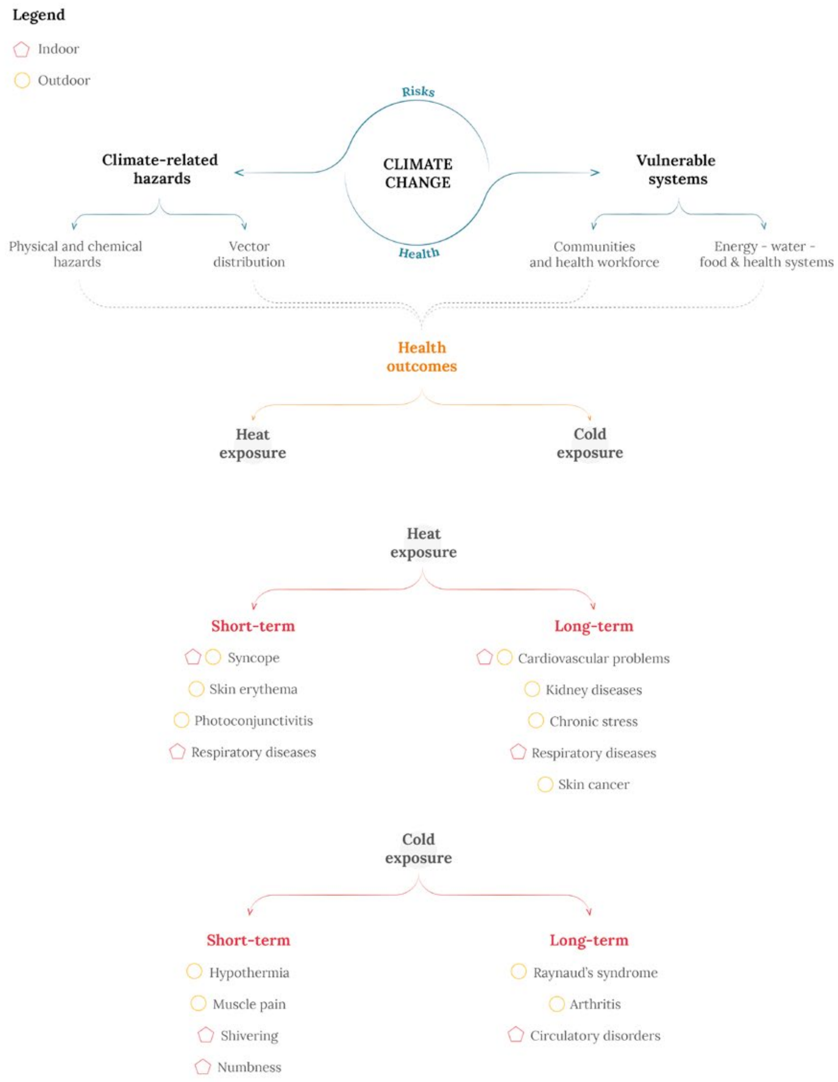


Figure 1. An overview of the impact of Climate Change (CC) on human health.

Heat exchange in the human body

The human body consists of a heat-generating core containing vital organs, surrounded by an external layer of tissues that insulate it from the environment. Although temporary conditions such as physical activity can cause fluctuations, body temperature typically remains at around 37°C (Bevilacqua & Piccioni, 2022). As homeothermic organisms, humans maintain a stable internal temperature through biological thermoregulation, which is controlled by the hypothalamus. In hot conditions, effective thermoregulation via sweating and evaporation is essential to preserve alertness and prevent accidents. (Bevilacqua & Piccioni, 2022). An unsatisfactory bodily reaction can result in serious conditions like heat exhaustion or heat stroke in tough work settings marked by extreme temperatures and ongoing heat exposure. Epidemiological studies conducted in several countries (Martínez-Solanas et al., 2018; Varghese et al., 2019; Marinaccio et al., 2019; Spector et al., 2019; Lee et al., 2019; Gariazzo et al., 2023; Di Biasi et al., 2023) have documented these effects. In addition to physiological effects, prolonged exposure to heat stress impacts cognitive and psychological functions. Specifically, research has shown impairments in reaction time, alertness and decision-making ability among workers (Mazloumi et al., 2014; Dutta et al., 2015; Rastegar et al., 2021). From a cognitive ergonomics perspective, these effects translate into an increased risk of human error, particularly when performing complex tasks.

The working population, particularly those in occupations that require protective clothing, is more susceptible to heat stress than the general public. This clothing often lacks breathability, trapping heat and humidity inside and impeding sweat evaporation, which significantly reduces the body's natural cooling mechanisms. As sweat accumulates without evaporating, core body temperature rises, increasing workers' vulnerability to heat-related strain (Amoadu et al., 2023). Amoadu et al. identify several occupational and individual risk factors that contribute to heat-related illnesses and their associated health outcomes. It emphasises the heightened vulnerability of specific groups–such as migrant workers, especially those employed in agriculture or other physically demanding outdoor jobs—who are disproportionately exposed to heat stress due to intense workloads and limited access to protective measures. It illustrates the main adaptation strategies adopted to date. These include hydration practices, resting in shaded or cooled areas and adjusting work schedules—none of which address the limitations posed by protective clothing. Ongoing anthropogenic global warming will substantially reduce physical work capacity (Ioannou et al, 2022). Therefore, preventive and adaptive strategies are essential for protecting worker health and maintaining productivity.

Heat stress in outdoor workers: risks and mitigation strategies

The relationship between CC and occupational heat strain among outdoor workers is well established, with the most probable physiological pathway involving progressive dehydration, physical fatigue, dizziness, cognitive impairment, reduced concentration, and general discomfort (Habibi et al., 2021). A recent review indicates that migrant and ethnic minority outdoor workers are disproportionately affected by occupational heat stress (Sharma & Anikeeva, 2025), due to multiple overlapping vulnerabilities, including precarious employment conditions, language and cultural barriers, limited access to health services, and inadequate living and working environments (van Selm et al., 2025). These findings underscore the need for tailored interventions and policies to address heat-related risks in vulnerable worker groups. Among these, construction workers are particularly vulnerable, as they almost always work outdoors—often during the hottest months—exposed to humidity, solar radiation, and intense physical exertion (Acharya et al., 2018). This combination of heat, humidity, solar radiation, and physical exertion hinders the body's ability to dissipate heat effectively by reducing sweat evaporation, leading to impaired thermoregulation and an increased risk of heat-related illnesses. Several studies have shown that solar ultraviolet rays are a key risk factor for skin cancer, specifically among outdoor workers (Slavinsky et al., 2024; Wittlich, 2022; Cherrie & Cherrie, 2022). Among that, Vernez et al. (2015) analyzed a sample of 889 individuals, considering two common postural scenarios in outdoor work: standing upright and bending the torso forward. The study identified the body areas most exposed to solar radiation and demonstrated how working posture can influence exposure levels. Graphs a, b and c (Figure 2) particularly confirm these findings, showing that the neck and upper shoulder areas are especially vulnerable among construction and road workers. Graph d shows the estimated average UV dose on different body parts across seasons, compared to UV radiation measured at ground level. While the ground consistently receives the full amount of incident solar radiation, the human body—being three-dimensional and in motion—exhibits variable exposure levels depending on the angle of solar incidence and the worker's posture.

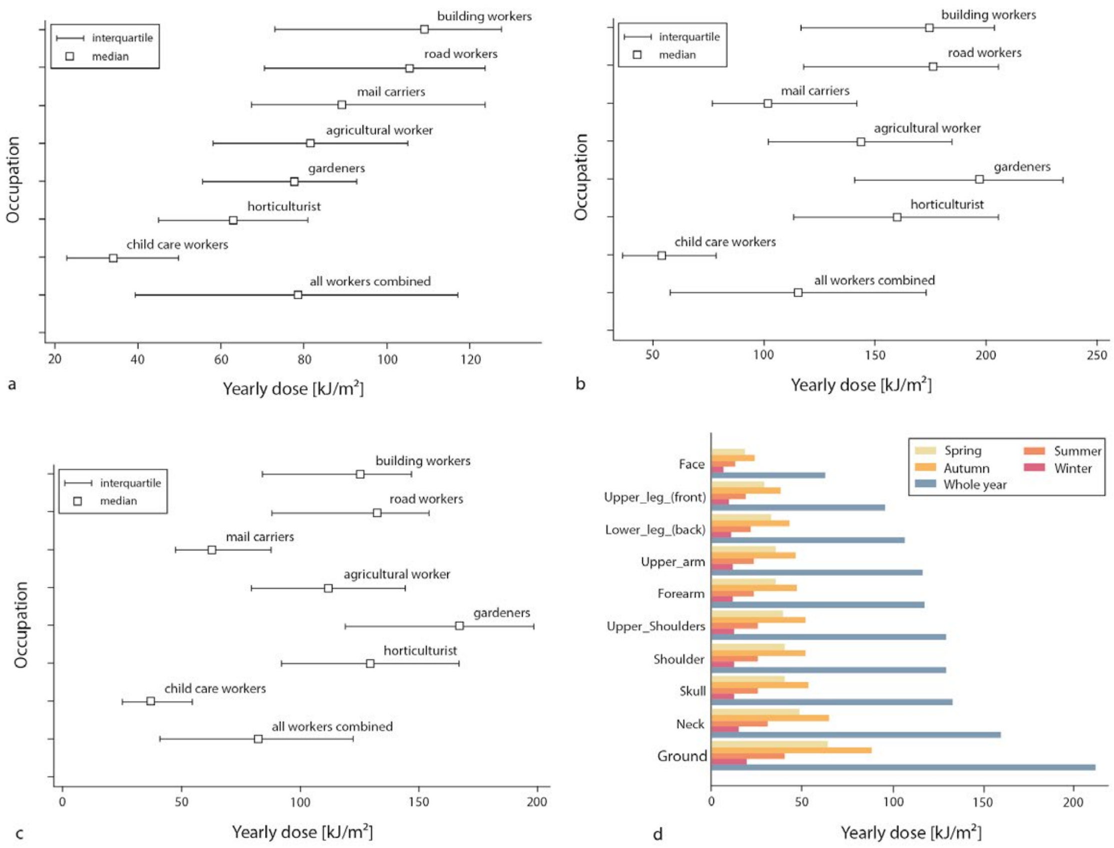


Figure 2. Estimated erythemal ultraviolet (UV) dose, expressed as yearly dose (in kJ/m²) [median (interquartile range)], by occupation and body site: (a) face, (b) neck, (c) top of shoulders. (d) Variation in estimated erythemal UV dose across different body sites, stratified by season and year. Source: Vernez et al., 2015.

These considerations highlight the importance of preventative strategies and the promotion of effective work practices to manage heat-related thermal stress. Occupational heat stress is addressed by international standards such as ISO 7243:2017, which provides a method for assessing environmental heat exposure using the WBGT index, and ISO 7933:2004, which estimates physiological strain through the Predicted Heat Strain (PHS) model. While ISO 7243 is based solely on environmental parameters, ISO 7933 incorporates individual factors such as metabolic rate and clothing insulation. Despite their technical relevance, the application and regulatory enforcement of these

standards vary considerably across countries and industrial sectors (Al-Bouwarthan et al., 2019).
In Italy, the reduction in productivity due to the need to limit heat exposure is estimated at an average of 6.5%, with peaks reaching up to 80% for physically demanding activities (Grifoni et al., 2021). In 2023, the National Research Council's Institute of BioEconomy (IBE) launched the Worklimate 2.0 project, supported by INAIL and other entities, to study the impact of extreme temperatures on workers' health and quantify the social costs of injuries. A web platform using the MOLOCH meteorological model was developed to provide personalised forecasts that support heat-related prevention strategies. Construction and infrastructure workers emerge as among the most at-risk categories, alongside agricultural workers and personnel in logistics and transportation (Beheshti et al., 2017; Del Ferraro et al., 2021; Grifoni et al., 2021). It is only through a process of acclimatisation that the human body can develop the capacity to tolerate tasks performed at elevated temperatures. While Personal Protective Equipment is essential for safety, it can impair the body's ability to cool itself by restricting airflow and trapping heat and moisture, thereby increasing the risk of heat stress. Regulatory frameworks, such as Italy's LD 81/2008, generally lack specific measures and offer only broad recommendations for heat exposure management. These include wearing lightweight, breathable, and light-colored clothing, using a hat with a visor and/or UV-filtering sunglasses, and applying high-protection sunscreen to exposed skin. Regulatory gaps highlight the need for more targeted guidelines. Moreover, common assumptions about clothing in hot climates are challenged by traditional desert attire. Though it may seem trivial, a study conducted as early as 1980 on Bedouins (Shkolnik et al.) reminds us that loose black garments can enhance thermal comfort by promoting airflow between fabric layers, thereby aiding heat dissipation. Although dark colours absorb more solar radiation than light ones, it is important to bear in mind that material, fit, and ventilation play a more significant role in cooling.

New frontiers for personal thermal management

The literature shows growing interest in innovative technologies and materials to protect workers from heat in high-risk environments. Wearable Technologies (WT) are particularly effective due to

their ability to monitor physiological and environmental parameters in real time (Bernasconi et al., 2022) and support the management of work-rest cycles and workloads, enhancing both well-being and productivity in high-temperature professional environments (Kato et al, 2025). They enable early detection of heat stress and the activation of preventive measures. By acting on the body, WT can provide localized and personalized cooling, as well as skin protection from UV radiation. Integrated into workwear through intelligent garments and smart textiles, WT help ensure comfort, breathability, and freedom of movement without compromising safety (Chan, Guo & Wong, 2015). The interaction between embedded sensors, actuators, and alert systems also allows for timely warnings to workers or safety personnel in case of risk, thereby preventing heat-related illnesses and injuries.
In this field, Smart Clothing (SC) plays a central role, representing the convergence of materials science, electronic engineering, and design. The literature identifies three key evolutionary trajectories: the degree of smartness, the level of technological integration, and the degree of energy autonomy. In terms of smartness, textiles are categorised as passive, active, or very smart based on their ability to sense, respond to, and adapt to external stimuli. Passive textiles do not autonomously respond to stimuli—their function is limited to sensing only. Active textiles are capable of detecting changes in body or environmental temperature and responding through integrated mechanisms such as controlled heating or cooling. Very smart textiles not only detect and respond, but also learn and dynamically adapt to body and environmental conditions, thanks to integrated sensors, actuators, microcontrollers, and adaptive logic. The level of integration has evolved across three generations: (i) electronic components externally applied to the fabric; (ii) components embedded within the textile structure; and (iii) electronic functionalities integrated into the fibers, enhancing comfort and aesthetic quality (Xiaopei and Li, 2019). This classification is relevant from an ergonomic perspective, influencing perceived comfort-defined as the absence of physiological, psychological, or physical discomfort (Kamalha et al., 2013)-as well as breathability, freedom of movement—dynamic wearability (Gemperle et al., 1998)—and long-term usability. SC and textiles for personal thermoregulation are not new to research. Over the past years, a growing number of studies have explored a variety of strategies and applications aimed at maintaining thermal comfort. Wu, Chen and Hsu (2023) provided a review in which four levels of personalised thermoregulation (PT) are identi-

fied: static, passively adaptive, actively adaptive and active (Figure 3). According to them, systems in the active category “rely on external work to enhance heat transfer, such as thermoelectric device (TED), liquid cooling circulation, and air ventilation”. Although these systems are capable of providing greater cooling capacity, they are now outdated and still consume a high amount of energy. While the proposed framework helps categorize existing solutions, it does not sufficiently address the trade-offs between thermal efficiency and wearability in real-world occupational settings.

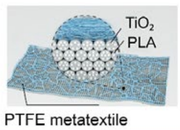
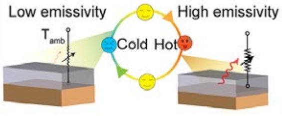
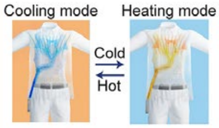
Wearable thermo-regulation	Static 	Passively adaptive 	Actively adaptive 	Active 
Energy consumption	Zero	Zero	Low	High
Cooling power	Middle	High	High	Very high
Sensor compatibility	No	No	Yes	Yes
Manufacturability	Easy	Moderate	Difficult	Difficult

Figure 3. Estimated erythemal ultraviolet (UV) dose, expressed as yearly dose (in kJ/m²) [median (interquartile range)], by occupation and body site: (a) face, (b) neck, (c) top of shoulders. (d) Variation in estimated erythemal UV dose across different body sites, stratified by season and year. Source: Vernez et al., 2015.

In the same year, Lei et al. (2023) offered a review of the recent advances in PT clothing, focusing on enhancing heat dissipation control between the skin and the immediate environment (garments that regulate thermal exchange through radiation[1] and conduction mechanisms). The review by Sajjad et al. (2023) addresses instead the growing need for energy-efficient personal thermal management devices, especially for individuals exposed to harsh or hot environments who require portable cooling solutions. It consolidates various cooling strategies, including active cooled garments (air, liquid, evaporative, micro fan ventilation, thermoelectric, vapor compression)[2], passive cooled garments (phase change materials, shape memory alloys), in-

1 Thermal radiation is a process of heat transfer through electromagnetic waves (infrared) emitted by any body with a temperature above absolute zero. In the case of the human body, the skin naturally emits heat in the form of infrared radiation toward *the surrounding environment. Garments for personal thermal management regulate this heat flow by mediating between the body and environment: they facilitate heat dissipation with infrared-transparent or reflective fabrics in hot conditions, limit heat loss with reflective materials in cold conditions, and dynamically adjust their thermal properties to optimize comfort based on environmental or physiological changes.*

[2] However, these solutions have been adopted for decades and generally suffer from low reliability relative to the operating times of individual systems. In particular, vapor compression refers to a cooling method that uses a refrigerant circulating through a closed loop, where the refrigerant absorbs heat by evaporating at low pressure and temperature, then releases heat when compressed and condensed at higher pressure. This process, commonly used in refrigerators and air conditioners, enables effective

telligent textiles, and hybrid cooling systems.

Each category's concepts, designs, applications, benefits, and limitations are discussed, along with radiative[3] and conductive cooling textiles. Despite the broad range of identified strategies, the actual long-term impact of each system on worker productivity and comfort remains unclear, an essential factor for large-scale industrial adoption. More recently, Zhang et al. (2024) provided a critical analysis of the strengths, limitations and ongoing challenges in SC designed for enhanced personal thermal management. Still, in 2024, Ma et al. provided a review of smart thermal management fabrics, distinguishing between passive and active systems based on their energy consumption (the presence or absence of external energy input) and by examining their mechanisms, research developments, advantages, and limitations. They highlighted the evolving role of e-textiles in health monitoring and energy harvesting, emphasizing the importance of maintaining wearing comfort in multifunctional applications.

Energy harvesting plays a crucial role in powering self-sustaining WT, meaning those capable of collecting energy from the surrounding environment without the need for an external power source. Among the different energy sources (heat from human body, light, vibrations, radio frequency) wearable thermoelectric generators (W-TEGs) stand out as a promising solution because they can produce hundreds of microwatts, which are sufficient to power different electronic sensors, such as electrocardiograph and pulse oximeters (Pang et al., 2023). Nevertheless, the reliability of energy harvesting under varying environmental and physiological conditions remains a key issue to address to ensure uninterrupted functionality.

As per product development, a smart cooling vest designed to reduce heat stress among construction workers was studied by Hossain et al. (2024). Focusing on active cooling mechanisms (Peltier fans[4]) and ergonomics, the research evaluates the vest's effectiveness in regulating body temperature and enhancing worker comfort and safety. A recent example of the integration of cooling fans was presented at Osaka Expo 2025 Designing future society for our lives (Fig. 4b), a jacket with built-in electric fans designed by Anrealage. In Japan's summer months, fan-equipped jackets have become a common sight among blue-collar workers. The technology, introduced in 2004 by former Sony engineer Hiroshi Ichigaya, founder of Kuchofuku, works by circulating air through the garment via two small fans at the waist, enhancing sweat evaporation and regulating body temperature. Now widely adopted by construction workers, traffic controllers, and other laborers in Japan—and increasingly entering markets such as China and the U.S.—this type of climate-responsive clothing has yet to see widespread use among the general public (Ogawa Clarke, 2024). This indicates that, beyond technical functionality, cultural and aesthetic factors still significantly influence the mainstream adoption of thermoregulatory clothing.

It is indeed a clear attempt to balance aesthetics with the ergonomic constraints of bulky ventilation components, reflecting ongoing efforts to improve thermoregulation without compromising comfort or mobility. An effort also evident in the Biosuit by Dainese and MIT (Figure 4b), designed to enable freedom of movement while maintaining safety and physiological stability of the astronaut, through body-mapped materials and tension lines that mirror muscular and skeletal anatomy. However, the design complexity and high cost of such systems pose major challenges for their translation into less extreme and more cost-sensitive contexts like construction or manufacturing.

A comparable design focus can also be found in the Liquid Cooling and Ventilation Garment (LCVG), an underlayer worn by astronauts. While the outer spacesuit provides insulation and helps retain body heat—except in areas exposed to extreme cold—active cooling is essential to prevent overheating. The LCVG meets this need by circulating water through a network of flexible tubes embedded in the garment, effectively dissipating excess heat. For the system to function properly, continuous and unobstructed water flow through inlet and return lines is critical. In both cases, the garments exemplify the complex interplay between technological performance and the human body in extreme environments (Smithsonian National Air and Space Museum, 2012).

cooling but requires complex components like compressors and condensers, which can limit durability and portability in wearable applications.

[3] Radiative cooling is a passive process where materials emit infrared radiation to dissipate heat without energy use. In clothing, radiative cooling textiles maximize body heat emission while minimizing sunlight absorption, helping wearers stay cooler in sunlight. These fabrics use coatings or fiber structures that reflect visible light but emit strongly in the infrared, offering an energy-free way to regulate body temperature. A comprehensive review on this topic is provided in the paper "Recent advancements in radiative cooling textiles for personal thermal management" by Jiang et al. (2024).

[4] A Peltier fan uses the thermoelectric effect to create cooling on one side of the garment while a built-in fan dissipates heat from the other side, enabling efficient temperature regulation.

***Figure 4a.** Biosuit by Dainese and MIT. Source: Newman, 2012; **Figure 4b**. A jacket with built-in electric fans designed by Anrealage, Osaka Expo 2025. Source: Burgos, 2025*

Figure 5. Liquid Cooling and Ventilation Garment (LCVG). Source: Smithsonian National Air and Space Museum, 2012

Similar, but different in the technological approach, is the study by Hong et al. (2019) that demonstrated a W-TEG that can deliver more than 10°C cooling effect with a high coefficient of performance[5] (COP > 1.5). It was the first to achieve long-term active cooling with high flexibility, due to a novel design of double elastomer layers and high-ZT rigid TE pillars[6]. In line with these developments, the study by Catarinucci et al. (2022) presented a preliminary validation of the software and sensor functionalities of a smart IoT system designed to improve workers' thermal comfort. It integrates customized, energy-efficient wireless sensors into graphene-based textiles, enabling optimal heat exchange and real-time monitoring of physiological parameters to detect signs of thermal stress. It features sensors, alert mechanisms for workers, and analytical tools for safety personnel to monitor and assess the collected data.

Regarding passive cooling systems, an Anti-Heat Stress Uniform for construction workers in hot and humid weather was first developed

[5] In thermodynamics, the Coefficient of Performance (COP) is an index used to evaluate the efficiency of a thermal system, such as a heat pump, refrigerator, or air conditioner. It expresses the ratio between the useful energy produced (transferred heat or cooling) and the electrical energy consumed to obtain it (Çengel & Boles, 2014).

by Chan et al. (2015) and subsequently adopted in Hong Kong's Construction Industry Council guidelines. In 2015, Tong et al. introduced a personal cooling technology based on an infrared-transparent yet visible-opaque fabric, enabling passive body cooling by allowing thermal radiation emitted by the human body to pass directly into the environment while maintaining a conventional textiles appearance. Made from synthetic polymer fibers engineered to maximize infrared transmittance (that refers to the ability of the fabric to allow infrared radiation—heat energy emitted by the human body—to pass through it) and minimize reflectance (which is the fabric's ability to reflect infrared radiation back toward the body), the fabric achieves high thermal efficiency. Although these materials show promising lab results, their long-term durability and effectiveness under dynamic and prolonged usage scenarios remain to be validated.

In 2019, Zang et al. developed an infrared-adaptive textile made of polymer fibers coated with carbon nanotubes. The yarns dynamically expanded and contracted in response to heat and humidity, altering fiber spacing. This adjustment improved breathability and modified the textile's infrared emissivity, enhancing heat exchange under hot and humid conditions. The self-adjusting emissivity offers promising potential for wearable thermal management. A similar concept is that of the Biologic Suit, developed by MIT's Tangible Media Group, which uses biohybrid fabrics with moisture-reactive bacterial cells that expand and contract in response to body heat and sweat, enabling dynamic ventilation and passive thermal regulation (Wang et al. 2017). More recently, the Central Leather Research Institute and the Desert Research Center in Cairo have developed a cooler leather (Tejonmayam, 2025) made by applying a coating of chemicals derived from paraffin and Porous Activated Carbon (PAC) to the outer surface. It can maintain a surface temperature at least three degrees lower than leather coated with only PAC. The key lies in the phase-change materials in the coating, containing substances that absorb and release heat during phase transitions, such as melting and solidifying.

[6] High-ZT rigid TE pillars are solid columns made of high-performance thermoelectric materials, designed to maximize the conversion of heat into electricity (or vice versa) while maintaining mechanical rigidity. They are used, for example, in thermoelectric generators, cooling devices, or sensors.

Discussion

Despite the benefits and the growing diffusion of WTs, several critical factors continue to hinder their widespread adoption and long-term integration in occupational settings. Field observations and direct dialogue with workers reveal a substantial cultural and informational gap: many users are unaware of existing wearable technologies (WTs) and express skepticism or discomfort toward unfamiliar devices. This perceived disconnect is often exacerbated by limited training and unclear added value, which together contribute to a widespread reluctance to adopt new solutions. Such attitudes highlight a systemic failure in participatory design processes, where experiential knowledge from end-users is insufficiently integrated. These cultural and cognitive barriers are compounded by unresolved technical challenges. From an ergonomics perspective, thermal comfort is frequently compromised by suboptimal materials and limited adaptability to individual variability. For instance, Phase Change Materials (PCMs), while effective under controlled conditions, have been associated with skin irritation when placed in high-contact areas such as the chest and back, suggesting a significant gap between laboratory testing and real-world usability. Air-based cooling systems present additional contextual limitations. When relying on ambient air, fluctuations in temperature, humidity, and purity may compromise effectiveness and limit scalability across different environments. Internal air circulation offers more consistent performance but tends to increase bulk and energy consumption. Current fan integrations remain largely external and cumbersome, limiting mobility and comfort. Similarly, liquid-based cooling systems, despite their heat dissipation capacity, raise concerns about added weight, potential leakage risks and chemical safety concerns, and maintenance complexity. These layered limitations (technical, ergonomic, and socio-cultural) underscore the need for an iterative, user-centered design methodology that balances thermoregulatory performance with wearability, simplicity, and trust. Finally, environmental sustainability remains a critical dimension in the development of wearable technologies (WTs). According to the Global E-waste Monitor (2022), the amount of electronic waste generated globally continues to rise, raising concerns about the long-term impact of all technology-intensive solutions, including WTs. Although many of the thermoregulatory systems discussed in this article (such as PCM-based garments, air-cooled vests, and liquid circulation devices) are not inherently electronic, their effective implementation increasingly relies on active components (fans, sensors, control units, batteries). If these elements are not designed for disassembly or reuse they may contribute to e-waste accumulation over time. Innovation in this domain must therefore be critically evaluated not only in terms of performance, but also of durability and sustainability across the entire product life cycle.

Conclusions

CC is reshaping the historical link between human labor and exposure to extreme environments. Higher and more unpredictable temperatures require an integrated approach to the prevention of thermal risks. In this context, WT and smart textiles offer new opportunities due to their ability to monitor and actively intervene in thermoregulation. Nevertheless, transitioning from experimental solutions to widely adopted and effective tools requires addressing key challenges, including device miniaturization, energy efficiency, ergonomic integration and scientific validation. In particular, future developments should aim to combine multiple thermal regulation mechanisms within a single fabric to enable broader industrial and everyday applications. Only through an interdisciplinary synergy between materials science, occupational medicine, engineering and public policies will it be possible to translate these innovations into concrete responses to the changed climate scenario, helping to protect the health and productivity of exposed people. Addressing these complexities will be essential for translating smart workwear from experimental prototypes into scalable, effective solutions for protecting vulnerable workers in an increasingly hostile climate.

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