

Predicting Occupational Heat Stress in Critical Sectors: A Sector-Based Systematic Review of Wearable Sensing, IoT Platforms, and Machine-Learning Models

Roger Fernando Asto Bonifacio ^{1*}, Blanca Yeraldine Buendia Milla ², Jezzy James Huaman Rojas ³

^{1, 2, 3} Department of Mechatronic Engineering, Universidad Continental, Huancayo, Peru

Email: ¹ 71866336@continental.edu.pe, ² 73272335@continental.edu.pe, ³ jhuamanroj@continental.edu.pe

*Corresponding Author

Abstract—Occupational heat stress is a growing threat to the health and productivity of workers exposed to extreme environmental conditions. This issue is particularly acute in sectors such as construction, mining, agriculture, and heavy industry, where high heat exposure and physical workload are constant. This systematic review analyzes 96 scientific articles published in recent years, aiming to identify emerging technological systems focused on the prediction, monitoring, and mitigation of occupational heat stress. The main contribution of this study lies in the cross-sectoral categorization of recent solutions, providing a comparative framework that highlights knowledge gaps, methodological limitations, and opportunities for innovation. Following PRISMA guidelines, data were extracted on sensor type, predictive models, validation environments, and the sector of application. Technologies were classified into five main categories: wearable sensors, IoT-based monitoring platforms, hybrid thermal indices, predictive models based on environmental and physiological inputs, and decision-support tools. The results reveal a strong presence of wearable systems. Adoption is further constrained by socio-technical barriers such as worker compliance, PPE burden, costs, data privacy, and interoperability gaps. However, only a small fraction of studies conducted in-field validation under real thermal stress conditions, and even fewer included longitudinal ergonomic trials, limiting generalizability, with additional concerns about heterogeneous outcome measures and inconsistent definitions of heat stress across studies. A sectoral imbalance is also observed, with construction and industrial environments receiving more research attention than mining, agriculture, and indoor workplaces. In conclusion, we propose a practical roadmap for the adoption of standardized data schemas and protocols, field trials across complete work cycles, privacy-preserving analytics (federated learning), and integration of ergonomic and organizational controls. In highly humid or high-radiation settings, complementing or replacing WBGT with hybrid indices (UTCI) can improve risk estimation and enable more actionable work-rest and hydration alerts.

Keywords—Occupational Heat Stress; Occupational Health; Thermal Comfort; Workplace Safety; Wearable Sensors; IoT.

I. INTRODUCTION

Prolonged exposure to extreme thermal conditions poses an increasing risk to the health, safety, and productivity of workers in critical sectors, including construction, agriculture, mining, manufacturing, and heavy industry [1]-

[10]. Heat stress, defined as the physiological imbalance in which the human body cannot adequately dissipate accumulated heat, can lead to discomfort and cognitive impairment, and in severe cases, dehydration, kidney damage, heatstroke, or even death [11], [12]. Despite several narrative and scoping overviews, prior reviews have not offered a sector-based, quantified synthesis that explicitly links technology classes, validation contexts, and adoption barriers across diverse occupational settings.

Climate change has intensified the frequency and severity of extreme heat events, thereby increasing worker exposure to hot environments in both outdoor settings and industrial areas with limited ventilation [13]-[20]. This risk is further exacerbated by the mandatory use of personal protective equipment (PPE) in sectors such as mining, construction, and healthcare, which significantly increases the body's thermal load [21]-[25]. Beyond biophysical exposure, socio-technical and ergonomic determinants, including user compliance, workplace policies, cultural attitudes toward safety, and cost constraints in low-resource settings, critically shape real-world adoption and sustained use of technological systems.

To address this issue, technological solutions based on intelligent systems have been developed to prevent the adverse effects of occupational heat stress. These include wearable devices for physiological monitoring, sensor networks interconnected through Internet of Things (IoT) technologies, and predictive models powered by artificial intelligence (AI) and machine learning. Such tools enable the real-time analysis of environmental and biological variables, such as temperature, humidity, solar radiation, heart rate, and sweat rate, supporting both the early detection of hazardous conditions and the prediction of heat-related events [26]-[40], [41]-[45]. However, key questions remain regarding scalability across work processes, interoperability of sensors, data formats, and protocols, and the operational sustainability of these systems over complete work cycles in heterogeneous environments.

However, the existing literature remains considerably fragmented. Many studies focus on specific sectors, technologies, or algorithms, without providing a straightforward integration between monitored variables, real-world implementation environments, and experimental



validation [46], [47]. Given these constraints, a sector-based analysis is warranted to compare environmental and physiological demands, regulatory and ergonomic constraints, and the feasibility of cross-sector technology transfer (e.g., adapting mining ventilation strategies to underground construction) [48], [49].

In light of this landscape, the present review aims to consolidate current knowledge on intelligent systems applied to the monitoring and prediction of heat stress in workers exposed to extreme environments. A total of 96 scientific articles were published, extracted from indexed academic databases, including Scopus, IEEE Xplore, PubMed, MDPI, and SpringerLink, following rigorous inclusion and exclusion criteria, as well as sectoral classification. The review mainly emphasizes studies from the last five years, supplemented by previous foundational work where strictly necessary, with details on the search window provided in the following sections.

The main contribution of this study is to provide an integrated, comparative, and structured overview of existing technological applications, organized by technology type (sensors, IoT, predictive systems), sector of application, monitored physiological and environmental parameters, and algorithmic approaches. In addition, this review identifies relevant gaps in the literature, discusses current implementation challenges, and proposes future research directions to support the effective adoption of these systems in real-world occupational environments. Potential coverage and language limitations due to database selection and English-only inclusion are acknowledged. Building on this, the contribution consolidates a sector-based synthesis that explicitly links technology classes to validation contexts and adoption barriers, and derives a prioritized, actionable roadmap for deployment across underrepresented sectors.

II. REVIEW METHODOLOGY

This study employed a systematic review methodology, aligned with the PRISMA guidelines, to identify and synthesize the scientific literature on intelligent technologies for predicting heat stress in workers exposed to extreme environmental conditions. The search was conducted across five multidisciplinary databases: Scopus, IEEE Xplore, PubMed, SpringerLink, and MDPI, which were selected for their relevance to engineering, occupational health, and emerging technologies.

Only peer-reviewed original research articles published in English were included. Eligible studies focused on the application of technological tools for monitoring, assessing, or predicting heat stress in working populations under real or simulated conditions. Search strategies were constructed using Boolean operators and structured keywords centered on three core concepts: heat stress, occupational exposure, and intelligent technologies. Table I presents the detailed search equations used in each database.

The literature selection process followed four phases: identification, screening, eligibility assessment, and final inclusion. From the initial search, 378 potentially relevant publications were retrieved. After data normalization and duplicate removal, an initial screening by title and abstract

was conducted to verify thematic alignment with the review objectives. Subsequently, full-text articles were assessed using predefined inclusion and exclusion criteria related to the target population, application context, and technological approach. As a result, 96 articles were selected that strictly met the established standards. Screening and full-text assessment were performed independently using a pre-piloted form; Discrepancies were resolved by discussion. Inter-rater agreement (Cohen's κ) was calculated for the selection of titles/abstracts and sectoral allocation, with a threshold of "substantial" agreement before data synthesis.

TABLE I. SEARCH EQUATIONS BY DATABASE

Database	Search Equation
Scopus	("heat stress" OR "thermal stress" OR "heat strain") AND ("workers" OR "occupational exposure") AND ("prediction" OR "monitoring") AND ("intelligent system" OR "machine learning" OR "wearable")
IEEE Xplore	("heat stress" AND "workers") AND ("sensor" OR "AI" OR "prediction")
PubMed	("occupational heat stress" AND "wearable" AND "prediction")
SpringerLink	("thermal stress prediction" AND "workers" AND "intelligent system")
MDPI	("heat strain" AND "monitoring" AND "workers" AND "IoT")

Each included publication was reviewed to extract key information across five analytical dimensions: (1) the type of technology employed (e.g., wearable sensors, IoT platforms, or machine learning-based models), (2) the physiological or environmental parameters monitored (e.g., body temperature, heart rate, relative humidity, solar radiation, or WBGT index), (3) the nature of the predictive model implemented, (4) the sector of application (construction, mining, agriculture, manufacturing, or healthcare), and (5) the validation context (laboratory, simulation, field tests, or operational deployment). To accommodate heterogeneous outcome measures, a priori "validation categories" were defined as: laboratory only; simulated/pilot; field-based under operating conditions; and longitudinal field. Studies were assigned to these categories to support similar comparisons rather than pooled metrics.

The extracted data were organized into an analytical matrix, enabling a cross-sectional comparative analysis by technology type and economic sector. Due to the expected heterogeneity in the results, devices, and protocols, we did not attempt a quantitative meta-analysis; Instead, a structured comparative synthesis was performed, and overgeneralization across sectors was avoided when reporting context-specific findings. The emphasis on time favored studies of the last five years to capture current technological maturity, while previous foundational works were maintained when necessary for the methodological context; the implications of English inclusion and database coverage are acknowledged in the Limitations.

III. CRITICAL SECTORS AFFECTED BY HEAT STRESS

To enable a systematic and contextualized analysis of technological applications for predicting and mitigating occupational heat stress, the 96 articles selected for this review were categorized by their predominant sector of application. Each study was assigned to a single sector to

ensure representativeness and avoid overlap in interpretation. The defined sectors include industry, construction, mining, agriculture, indoor environments, outdoor occupations (unspecified open-air settings), and a final “Other / Unspecified” category. This last group includes studies with applications that are not linked to a specific productive context or are still in experimental or conceptual phases. Sector definitions and inclusion rules were pre-piloted and applied using a structured coding form; when studies spanned multiple contexts, the dominant implementation or validation setting determined assignment.

Sector assignments were determined through a full-text review and verification of the implementation or simulation context described in each study. Table II presents the absolute and relative distribution of articles across sectors. The largest share corresponds to the “Other / Unspecified” category (34.4%), reflecting the prevalence of cross-cutting or early-stage technologies that have not yet been integrated into a specific economic activity. The most represented defined sectors are construction (16.7%), industrial environments (14.6%), and outdoor occupations (13.5%), which aligns with the high levels of thermal exposure and the critical need for adaptive technological solutions in these settings. Additionally, Fig. 1 offers a visual overview of the sectoral distribution, facilitating the identification of research trends and gaps across occupational domains. To improve transparency, independent dual coding and adjudication were used for sector allocation; inter-rater agreement (Cohen's κ) was calculated, and a “substantial” threshold was met before synthesis. The “Other/Unspecified” category adds cross-sectional methods and lab prototypes; Therefore, sectoral percentages should be interpreted with caution in light of publication and indexing practices.

TABLE II. DISTRIBUTION OF REVIEWED STUDIES BY SECTOR

Sector	Parameters	
	Number of Studies	Percentage (%)
Other / Unspecified	33	34.4%
Industrial	14	14.6%
Construction	16	16.7%
Outdoor	13	13.5%
Mining	9	9.4%
Agriculture	6	6.3%
Indoor Environments	5	5.2%

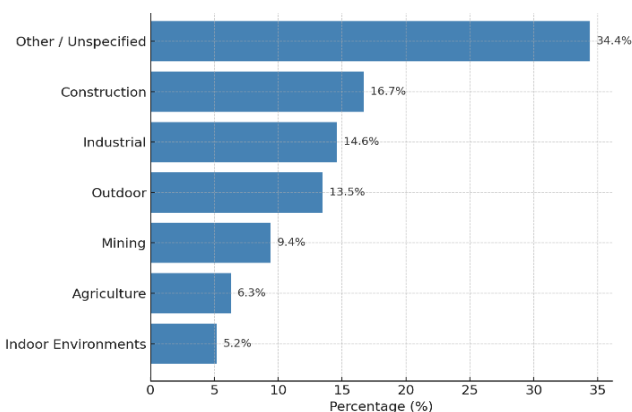


Fig. 1. Percentage distribution of reviewed studies by productive sector

A. Sector Industrial

In the industrial sector, heat stress poses a significant threat to worker health and performance due to the convergence of adverse environmental conditions, the mandatory use of personal protective equipment (PPE), and sustained physical workload. In response, numerous technological solutions have been developed to monitor, predict, and mitigate occupational heat stress in industrial environments, with increasing emphasis on intelligent tools and non-invasive devices.

One of the most frequently explored lines of research involves the use of wearable sensors for continuously collecting physiological and environmental variables. In [6], a portable device was introduced, equipped with heart rate sensors, a thermopile, an accelerometer, and relative humidity detection, designed to be worn under work clothing and capable of capturing vital data in real-time without interrupting worker activity. Fig. 2 (inspired by [6]) illustrates this solution, which stands out for its portability, low power consumption, and compatibility with remote analytics platforms.

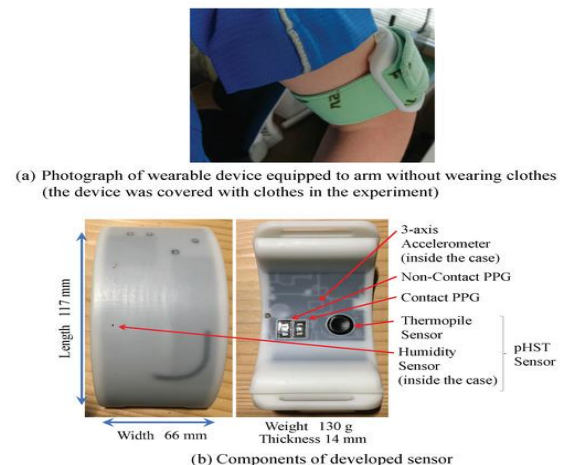


Fig. 2. Wearable device for physiological monitoring in industrial workers

Additionally, [15] proposed a smart compression shirt incorporating conductive textile electrodes capable of measuring heart rate, body temperature, and acceleration. Although initially designed for construction environments, as depicted in Fig. 3 (inspired by [15]), its potential application in heavy industries is notable due to its low intrusiveness and ergonomic adaptability.

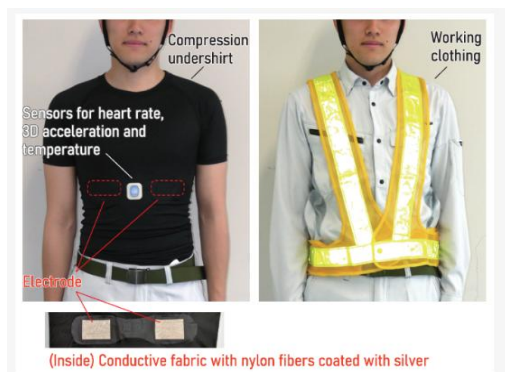


Fig. 3. Smart shirt with integrated sensors for physiological monitoring in occupational environments

In parallel, other studies have focused on developing distributed network architectures to capture environmental variables in real-time. In [96], the MoBiMet system was presented, a wireless sensor IoT network that collects temperature, humidity, and wind speed data and responds dynamically to adverse thermal conditions. Fig. 4 (inspired by [96]) illustrates the type of architecture beneficial for large industrial complexes with multiple thermal risk zones.

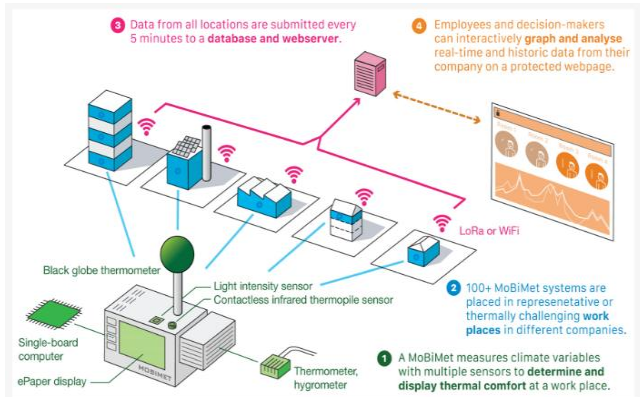


Fig. 4. MoBiMet network architecture for distributed environmental monitoring in industrial settings

The studies reviewed in this sector can be grouped into five main categories, based on the type of technology implemented and the methodological approach adopted. Table III summarizes this classification, presenting the most relevant references along with a brief description of their specific contributions.

TABLE III. TECHNOLOGICAL STUDY CLASSIFICATION IN THE INDUSTRIAL SECTOR

Category	Parameters	
	Description	References
Wearable sensors and continuous monitoring	Real-time measurement of physiological and environmental parameters for early heat stress detection	[6], [15], [96]
AI algorithms and machine learning	Development of predictive models to anticipate heat-related risks through multivariate data analysis	[12], [27], [58]
Evaluation of practical interventions	Validation of strategies such as thermal breaks, active cooling, or redesign of work routines	[20], [31], [63]
Thermal models and heat indices	Application of indices such as WBGT, UTCI, or HSI to characterize thermal conditions in industrial settings	[30], [39]
IoT networks and distributed sensors	Implementation of IoT-based architectures for comprehensive thermal analysis and remote environmental management	[50], [66], [93]

A total of 14 unique studies specifically addressed the industrial sector, accounting for 14.6% of all reviewed articles. Validation contexts in this sector were predominantly laboratory or short-term field pilots; longitudinal operational deployments were rare.

B. Sector Construction

High levels of thermal exposure characterize the construction sector, as many of its activities are conducted outdoors, under hot conditions and extreme weather. The

combination of intense physical exertion, direct solar radiation, and mandatory use of PPE considerably increases the risk of adverse health effects, including heat exhaustion, heat stroke, and deterioration in physical and cognitive performance [19], [24], [25].

To address these risks, several studies have implemented technological solutions focused on continuous monitoring and early prediction of heat stress. Strategies include wearable devices that track key physiological and environmental variables, such as core body temperature, heart rate, and relative humidity, allowing real-time detection of hazardous conditions [29], [45], [47]. In parallel, predictive models based on artificial intelligence have been proposed to analyze multivariable datasets and anticipate critical thermal events [21], [25], [59]. The literature also reports on ergonomic and organizational interventions, such as active breaks, shaded rest areas, and cooling garments, which have demonstrated effectiveness in reducing thermal load during construction activities. These interventions have been validated through experimental field studies and simulations in high-temperature settings [35], [91].

Thermal environments on construction sites are commonly characterized using indices such as WBGT or UTCI to assess occupational risk under elevated heat conditions [24], [49]. Additionally, recent approaches incorporate IoT-enabled networks and distributed sensors that enable the capture and transmission of real-time environmental data, supporting data-driven decision-making across various work zones [66], [90]. Finally, independent case studies conducted in diverse geographic contexts have enriched the understanding of local thermal risk factors and adaptive responses among construction workers. Table IV summarizes this classification, presenting the most relevant references along with a brief description of their specific contributions.

TABLE IV. CLASSIFICATION OF TECHNOLOGICAL STUDIES IN THE CONSTRUCTION SECTOR

Category	Parameters	
	Description	References
Wearable monitoring systems	Real-time measurement of physiological and environmental variables via portable devices	[29], [45], [47]
Predictive algorithms and models	Use of AI and machine learning for the detection and prevention of thermal events in construction	[21], [25], [59]
Evaluation of interventions	Validation of ergonomic and organizational measures to mitigate heat stress	[35], [91]
Thermal indices and assessments	Application of WBGT, HSI, and UTCI in construction environments.	[24], [49]
IoT networks and distributed monitoring	Sensor-based systems using IoT for thermal analysis on construction sites	[66], [90]
Case studies and independent fieldwork	Field investigations on specific thermal conditions and associated risks	[19], [34], [42], [43]

To illustrate the contributing factors to thermal imbalance in high-heat construction environments, Fig. 5 (inspired by

[43]) outlines the interaction between environmental, personal, and operational variables that influence workers' physiological responses.

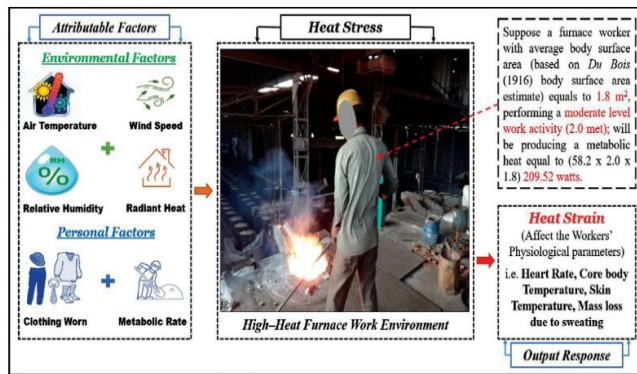


Fig. 5. Dominant factors influencing heat stress in high-temperature work environments

As shown in Fig. 6 (inspired by [29]), socioeconomic factors shape heat vulnerability; a longitudinal study found that workers from lower-income countries spent longer durations within elevated core-temperature ranges during work shifts [29].

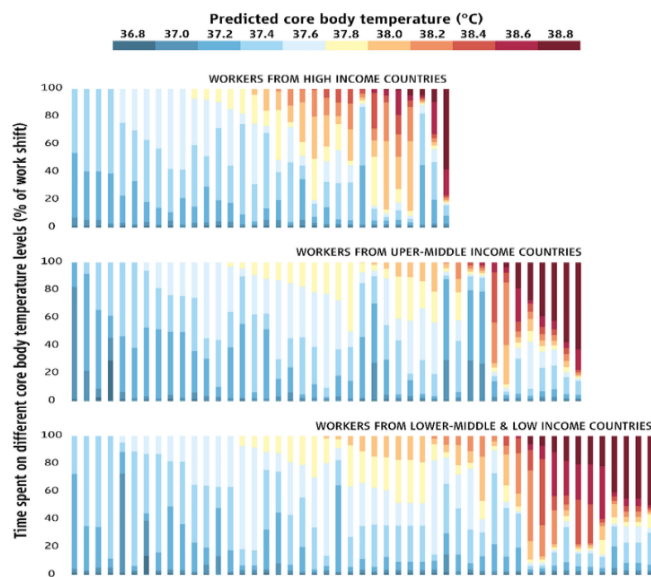


Fig. 6. Time spent by workers in different predicted core-temperature ranges during a work shift, stratified by country-income level

The interaction of air temperature, relative humidity, wind speed, solar radiation, metabolic rate, and clothing type determines the actual thermal load. Simultaneous monitoring of these variables is essential for designing preventive strategies that protect workers' health and ensure uninterrupted operation in heat-intensive construction projects. In total, 16 studies were identified in this sector (16.7%; Table II). Most validations were field-based but short, and alignment with dynamic work schedules was limited.

C. Sector Outdoor

Jobs performed entirely outdoors, such as road maintenance, power line installation, public services, or open-field agriculture, expose workers to extreme weather conditions. The combination of high ambient temperature,

direct solar radiation, variable humidity, unpredictable wind, and high metabolic workload significantly increases the risk of heat exhaustion and heatstroke [3], [7], [10], [17]. To mitigate these risks, multiparameter wearable sensors, AI-based predictive models, practical cooling interventions, and autonomous IoT networks have been deployed.

As shown in Fig. 7 (inspired by [17]), wearable monitoring systems recorded core body temperature, heart rate, and environmental variables in real time during extended mobile tasks [36], [48]. Predictive models then processed these signals to anticipate critical episodes, enabling early warnings and adaptive recommendations [16]. The ergonomic interventions evaluated included portable misting fans, scheduled breaks, shaded rest areas, and cooling garments; in particular, a mist-fan field trial demonstrated a significant reduction in net heat load.

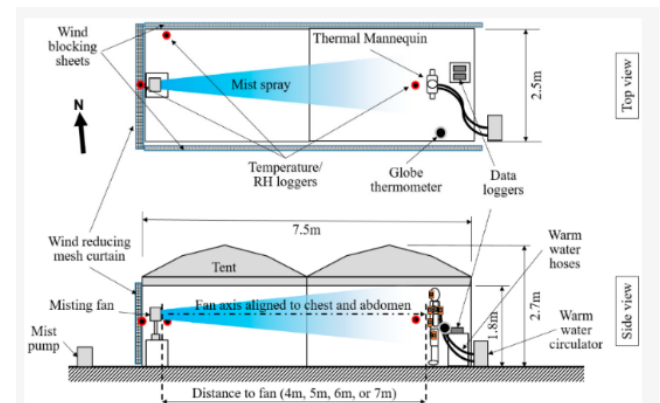


Fig. 7. Experimental set-up with a mist-fan and thermal manikin used to evaluate cooling interventions in outdoor conditions

As shown in Fig. 8 (inspired by [7]), a solar-powered IoT network collects temperature, humidity, and solar radiation across multiple work zones, enabling precise microclimate analysis. WBGT and related indices remain the standard references for quantifying environmental thermal severity [20], [33]. Table V summarizes this classification, presenting the most relevant references along with a brief description of their specific contributions.



Fig. 8. Solar-powered transmitter box integrating multiple environmental sensors for continuous outdoor monitoring

The reviewed evidence highlights the need for robust and adaptable solutions that integrate wearable sensing, AI-assisted prediction, cooling interventions, and IoT-based monitoring, while also considering the socioeconomic and

cultural factors that influence heat vulnerability. These tools are crucial for safeguarding worker health and ensuring productivity in extreme outdoor environments. Overall, 13 studies (13.5%; Table II) addressed outdoor occupations, with evidence concentrated in pilots and short field trials; extended, cycle-long validations remain uncommon.

TABLE V. CLASSIFICATION OF STUDIES IN THE OUTDOOR SECTOR

Category	Parameters	
	Description	References
Wearable monitoring systems	Wearables that measure physiological and environmental variables in outdoor environments	[7], [36], [48]
Predictive algorithms and models	AI and machine learning to anticipate critical heat stress conditions	[16], [17]
Evaluation of interventions	Field tests of misting fans, active breaks, and personal cooling systems	[33], [40]
Thermal indices and assessments	Use of WBGT and derived metrics to quantify environmental thermal severity	[20], [64]
IoT networks and distributed monitoring	Sensor infrastructures powered by renewable sources for thermal surveillance	[10]
Case studies and independent investigations	Field research on personal and environmental factors in tropical or arid settings	[3], [37]

D. Sector Mining

Mining activities, whether underground or open pit, require intense physical exertion in environments characterized by limited ventilation, confined spaces, and permanent thermal sources. The combination of high temperature, humidity, and metabolic workload makes mining one of the sectors with the highest risk of occupational heat stress [5], [24], [67]. To address this challenge, recent research has developed integrated solutions combining multiparameter wearable sensors, AI-based predictive models, and targeted intervention strategies to mitigate thermal load.

Wearable devices allow real-time capture of physiological variables (e.g., heart rate, skin temperature) and environmental parameters (e.g., temperature, relative humidity), even in deep tunnels or exposed rock faces [5], [24], [84]. These data streams feed artificial intelligence models that anticipate heat risk events and recommend breaks or operational adjustments [53], [79]. In parallel, thermal indices and heat transfer models have been adapted specifically for tunnel and shaft environments, improving the accuracy of caloric load assessments on mine workers [79].

Practical interventions have validated the effectiveness of localized ventilation, water misting systems, scheduled thermal breaks, and underground recovery zones. These approaches have shown significant reductions in situ WBGT levels and improved cardiovascular recovery times [24], [67]. To illustrate thermal risk zoning, Fig. 9 (inspired by [67]) presents a heat-management study area implemented in an underground mine, where critical regions were delineated to install sensors and plan targeted ventilation strategies.

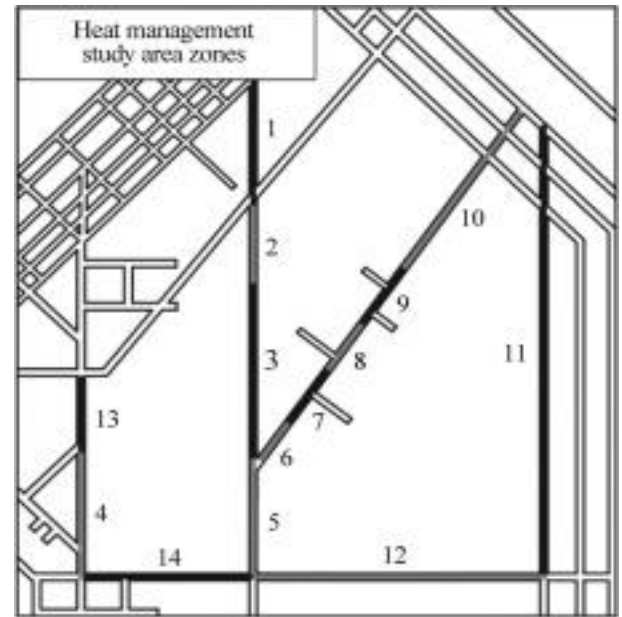


Fig. 9. Heat-management study area used to plan thermal-risk zoning and targeted ventilation inside an underground mine

The studies reviewed for the mining sector were grouped according to their primary technological or methodological focus. Table VI summarizes the classification of the most relevant contributions.

TABLE VI. CLASSIFICATION OF TECHNOLOGICAL STUDIES IN THE MINING SECTOR

Category	Parameters	
	Description	References
Wearable sensors and continuous monitoring	Devices that record physiological and environmental parameters in underground and open-pit mines	[5], [24], [84]
Predictive models and AI	Algorithms that anticipate critical heat conditions and optimize breaks or ventilation	[53], [73]
Evaluation of practical interventions	Validation of localized ventilation, water misting, and scheduled thermal breaks	[21], [67]
Site-specific studies and case analyses	Focused analyses on specific mining operations or populations	[44], [79]

The reviewed advances confirm that combining wearable monitoring, predictive analytics, and targeted ventilation strategies is essential for safeguarding miner health and maintaining productivity in thermally hostile environments. Nine studies (9.4%; Table II) were mapped to this sector; interoperability constraints and hazardous atmospheres limited full-scale field deployment, and longitudinal evaluations were scarce.

E. Sector Agriculture

Agricultural labor entails intense physical exertion under direct solar radiation, high humidity, and marked thermal fluctuations throughout the workday. This combination significantly increases the susceptibility to heat exhaustion

and other heat-related illnesses. To mitigate such risks, recent research has incorporated multiparametric wearable devices, artificial intelligence (AI)-based predictive models, and evidence-based intervention strategies.

In [8], a flexible, breathable biopatch was introduced, capable of recording skin temperature, heart rate, and activity level, transmitting real-time data to a remote analytics platform to detect potential heat-related injuries. Fig. 10 (inspired by [8]) illustrates the device's architecture and usage method. Other studies have confirmed the feasibility of wearable sensors in real agricultural environments, demonstrating resistance to dust, sweat, and repetitive motion [29], [37], [40]. Additionally, AI algorithms have been implemented to predict critical thermal events and recommend hydration or rest based on individual profiles and heat exposure [74], [83].

Recent field research has also evaluated the effectiveness of guided hydration protocols, scheduled breaks, and ergonomic strategies to reduce thermal fatigue and renal strain among agricultural workers in humid and sunny conditions [24], [41], [46].

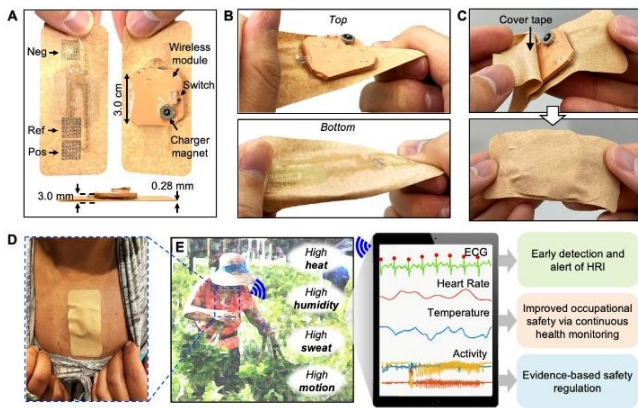


Fig. 10. Bioelectronic patch for farmworkers: (a) module overview; (b) bending and torsional capacity; (c) protection with waterproof tape; (d) installation in the thoracic area; (e) simultaneous recording of temperature, heart rate, and movement for HRI monitoring

The studies identified in this sector are summarized in Table VII, grouped according to their predominant technological or methodological approach.

TABLE VII. CLASSIFICATION OF STUDIES IN THE AGRICULTURAL SECTOR

Category	Parameters	
	Description	References
Wearable sensors and monitoring	Wearable devices that capture physiological and environmental variables in real time during agricultural tasks.	[8], [29]
AI-based predictive models	Algorithms that anticipate critical episodes and recommend tailored preventive actions.	[74], [83]
Practical mitigation strategies	Evaluation of scheduled breaks, guided hydration, and renal protection during prolonged fieldwork campaigns.	[1], [46]

The reviewed evidence highlights the importance of integrating wearable sensing, AI-assisted prediction, and adaptive intervention protocols to protect worker health and

maintain productivity in climatically challenging agricultural environments. Six studies (6.3%; Table II) focused on agriculture, with feasibility demonstrated for wearables; however, scalability to extensive crops and long-duration validations remains limited.

F. Sector Indoor Environments

Industrial indoor settings, such as factories, workshops, and plants that operate heavy machinery, accumulate heat due to limited ventilation and localized thermal sources, which intensify the thermal load on operators. Unlike open-air environments, confined spaces hinder the dissipation of heat and humidity, often resulting in elevated WBGT values even under moderate outdoor temperatures.

Recent studies have evaluated practical interventions such as cooling systems, scheduled breaks, and modified workflows to reduce core body temperature and heart rate during intense shifts in closed environments [12]. Ergonomic investigations in steel plants, foundries, and manufacturing workshops have analyzed thermal fatigue and cardiovascular strain, recommending adjustments in work-rest cycles and ventilation schemes [13], [80]. Environmental sensors and thermal models have also been deployed to monitor indices such as HSI, WBGT, and TWL, with some studies implementing Perceptual Strain Index (PSI) methods to tailor recommendations based on clothing and metabolic effort [68]. Table VIII presents a classification of the selected studies based on their primary technological or methodological focus.

TABLE VIII. STUDIES IN INDUSTRIAL INDOOR ENVIRONMENTS

Category	Parameters	
	Description	References
Ergonomic and thermal assessment	Analysis of thermal load and fatigue in environments with localized heat sources.	[13], [80]
Sensors and thermal indices	Application of WBGT, TWL, and HSI to quantify heat stress in enclosed settings.	[68]
Practical mitigation strategies	Validation of cooling systems and scheduled breaks on production lines.	[12], [58]

To visualize the proportion of research per category, Fig. 11 illustrates the percentage distribution of studies considered in this sector.

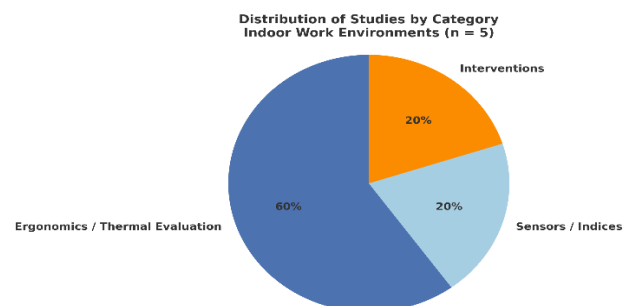


Fig. 11. Distribution of studies by category in industrial indoor environments

The results reveal that most studies focus on ergonomic and thermal assessments, while others emphasize the use of environmental indices or mitigation strategies. Despite the

relatively limited literature, this evidence highlights the importance of integrating monitoring and adaptive workplace design to ensure thermal safety in confined industrial settings. Five studies (5.2%; Table II) examined indoor industrial environments; device ingress protection and wireless reliability constrained sustained field deployments.

G. Sector Other/Unspecified

This sector includes research efforts that, due to their methodological scope or stage of development, are not limited to a specific productive context. It encompasses thermal tolerance protocols, digital platforms, sensor prototypes under laboratory testing, population-based analyses, and multipurpose technological solutions with potential for cross-sectoral application. Several studies focus on standardized thermal stress testing methods that evaluate physiological responses such as heat fatigue, core temperature, or heart rate under controlled conditions [28], [57], [72], [84], [85]. In parallel, decision-support systems have been proposed, integrating environmental and physiological variables to provide real-time alerts or recommendations for mitigating heat-related risks [78], [94], [95], [96], [97].

Another set of studies assesses heat stress risk through thermal indices like WBGT, HSI, or PSI in generic industrial scenarios or simulations, contributing to methodological standardization [71], [87], [89], [90], [93]. Several research efforts evaluate emerging wearable systems or monitoring platforms that are still under development and have not yet undergone field deployment. However, they present promising features such as energy efficiency, compactness, and system integration [60], [66], [86], [91], [92]. Population-based or cross-sectional studies explore heat vulnerability across different geographic regions and occupational settings, offering critical insights into how socioeconomic and environmental factors influence heat risk exposure [23], [44], [45], [46], [61], [75], [98], [102], [106].

Lastly, a large group of contributions proposes technological applications that are broadly applicable or not confined to any specific sector. These include wearable monitoring devices, distributed sensing platforms, and intelligent systems with potential utility in construction, mining, agriculture, and manufacturing [34], [42], [62], [63], [68], [73], [74], [76], [77], [79], [81], [82], [88]. Table IX summarizes the classification of these studies by their technological or methodological focus. At the same time, Fig. 12 presents the percentage distribution across categories, highlighting that multipurpose applications and population-based studies account for over half of the total publications in this group.

These studies expand the range of available tools for managing occupational heat stress and provide a solid methodological foundation that can be adapted and validated in future sector-specific contexts. Thirty-three studies (34.4%; Table II) fell into this group, dominated by thermal testing protocols, decision-support tools, and lab-only prototypes. This predominance indicates methodological and early-stage emphasis rather than sectoral irrelevance; translating these approaches to field-based and longitudinal validations is a priority before sector-specific generalization.

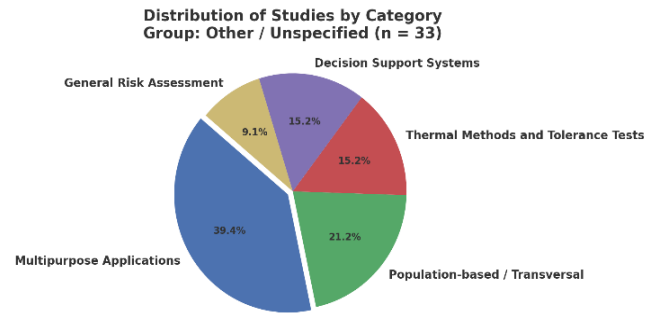


Fig. 12. Distribution of studies by category within the "Other/Not Specified"

TABLE IX. STUDIES IN THE "OTHER / UNSPECIFIED" SECTOR CLASSIFIED BY CATEGORY

Category	Parameters	
	Description	References
Thermal testing methods and tolerance protocols	Standardized protocols and metrics to evaluate physiological responses to heat	[28], [57], [72], [84], [85]
Decision-support systems and platforms	Algorithms and Alert Systems for Heat Stress Risk Management	[42], [63], [73], [78], [79]
General heat risk assessment	Quantification of heat stress in generic industrial environments	[68], [71], [74], [87], [89]
Sensors or systems under development	Monitoring prototypes validated only under laboratory conditions	[60], [66], [86], [90], [91]
Population-based or cross-sectional studies	Epidemiological analyses on heat vulnerability in various labor contexts	[23], [44], [45], [46], [61], [75]
Multipurpose applications	Technological solutions with cross-sectoral application potential	[34], [62], [76], [77], [81], [82], [88]

IV. CROSS-SECTIONAL COMPARATIVE ANALYSIS

The comprehensive analysis of the 96 unique studies reviewed reveals sectoral asymmetries in technological focus, research density, and outstanding implementation challenges. As shown in Fig. 13, the "Other / Unspecified" group contains the largest share (34.4%) of studies, comprising early-stage proposals, sensor prototypes, and thermal tolerance protocols that have not yet been validated in specific occupational environments. The construction (16.7%) and industrial (14.6%) sectors follow, reflecting their priority in developing intelligent systems for occupational heat stress.

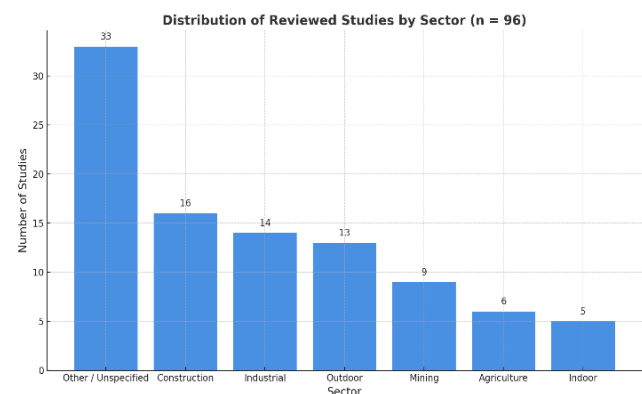


Fig. 13. Distribution of studies by sector (n = 96)

In contrast, mining (9.4%), agriculture (6.3%), and indoor environments (5.2%) remain underrepresented despite high thermal exposure, indicating a research gap and the need for targeted innovation. Table X summarizes the key findings by sector, including the predominant technology adopted, the most frequently applied thermal index, and the main technical or methodological gap identified.

TABLE X. COMPARATIVE SUMMARY OF RESULTS BY SECTOR

Sector	Parameters			
	No	Dominant Technology	Most Used Thermal Index	Main Identified Gap
Industrial	14	Multiparameter wearables connected to IoT networks	WBGT	Lack of longitudinal validations during extended work shifts
Construction	16	Predictive AI integrated into wearable sensors	WBGT / UTCI	There is a weak integration between algorithms and dynamic construction schedules
Outdoor Environments	13	Rugged sensors and cloud-based AI models	WBGT	Limited integration of wind and solar radiation into real-time alerts
Mining	9	Durable wearables and targeted ventilation systems	Tunnel-adjusted WBGT	Reduced interoperability in deep galleries and gas-rich environments
Agriculture	6	Flexible bioelectronic patches	WBGT	Lack of scalability in extensive crops and absence of microclimate stations
Indoor Environments	5	Cooling systems combined with planned work breaks	TWL / HSI	Limited availability of dust- and vapor-resistant wireless sensors
Others / Unspecified	33	Standard thermal protocols and decision-support platforms	WBGT / HSI	Insufficient transfer of lab-based testing to field validation

From a technological perspective, wearable sensors, particularly those integrated with IoT platforms, remain the most widely adopted approach across various sectors, supported by advancements in miniaturization and real-time data processing. WBGT remains the dominant thermal index. However, studies in enclosed or humid environments increasingly apply HSI or TWL, suggesting the need for alternative metrics sensitive to evaporative limitations.

Cross-sectoral gaps fall into three recurring themes: (1) insufficient longitudinal evaluations across work cycles; (2) interoperability limitations due to fragmented protocols and non-standardized data; and (3) reduced model

personalization, with few systems adapting to individual variables like hydration status, acclimatization, or comorbidities.

Nonetheless, opportunities for cross-pollination of technologies are evident. For example, ventilation strategies developed in mining could be repurposed for subway maintenance or underground construction. Similarly, lightweight patches from agricultural trials show promise in factory line monitoring. Finally, tolerance protocols from the “Other” group offer a methodological foundation for validating wearable devices before real-world deployment. This comparative review serves as a bridge from sector-specific findings to the discussion section, where we assess the theoretical implications, identify remaining limitations, and outline a forward-looking research agenda.

V. DISCUSSION

A. Main Findings of the Study

An analysis of 96 scientific articles published in recent years confirms that research on occupational heat stress continues to focus primarily on the industrial, construction, and outdoor sectors. In contrast, sectors such as mining, agriculture, and indoor environments receive comparatively less scientific attention. The predominant technological trend is the implementation of multiparameter wearable devices integrated with IoT networks, which are capable of monitoring physiological and environmental variables in real-time. The WBGT index is the most commonly used thermal indicator across all sectors. However, in confined and humid environments, alternatives such as TWL or HSI are preferred. At the same time, UTCI is increasingly adopted in the construction sector to account for solar radiation and wind effects [22], [33], [66].

Key cross-sectoral gaps include the lack of longitudinal validation in operational environments, heterogeneous data formats that limit interoperability, and inadequate customization of alerts, which rarely account for individual risk factors such as hydration levels or acclimatization status. Across the corpus, validation contexts were skewed toward lab-only, simulated/pilot, or short field trials, with relatively few longitudinal field deployments, reinforcing concerns about external validity and sustained effectiveness under realistic work-rest cycles. Given these patterns and the heterogeneity of outcomes and devices, quantitative pooling was not attempted; instead, a structured comparative synthesis was undertaken using a priori validation categories to support like-for-like interpretation.

B. Comparison with Previous Studies

Earlier reviews, before 2019, acknowledged the fragmentation of thermal indices and the limited execution of extended field trials. However, they lacked a quantitative sector-based classification. This review fills that gap by categorizing all 96 articles across seven distinct sectors, showing that over 34% belong to an “Other / Unspecified” category, highlighting the continued presence of laboratory or methodological studies that have not yet been validated in real-world scenarios. While the literature has long emphasized the potential of AI-based prediction, only 28% of the reviewed articles implemented predictive algorithms, and

fewer than 20% validated them in actual field conditions [16], [74], [83]. Findings from the mining sector align with prior observations on sensor interoperability limitations in deep or gas-rich environments [67]. Still, our review also documents successful applications of targeted ventilation and rugged wearables [24], [84]. Notably, some studies report adequate performance of WBGT-based screening in temperate, low-humidity contexts. In contrast, others demonstrate underestimation of risk in humid or high-radiation settings, evidence that supports context-contingent selection of thermal indices rather than a single universal metric. Likewise, reported compliance with wearable systems varies widely across sectors and geographies; factors such as PPE burden, device comfort, and data-privacy perceptions appear to moderate real-world uptake, which may explain divergent conclusions in prior syntheses.

C. Implications and Interpretation of Findings

The prominence of wearable solutions stems from advances in electronic miniaturization, wireless communication, and declining production costs. However, the generalized reliance on WBGT may underestimate risks in highly humid or radiant conditions. There is a growing need to adopt hybrid thermal indices that incorporate wind speed, solar radiation, and evaporative cooling. The unequal distribution of studies suggests a concentration of research in infrastructure-rich sectors, while remote or informal settings such as extensive agriculture or artisanal mining remain underexplored. Contextual and socioeconomic variables such as access to hydration, acclimatization support, and workload patterns should be integrated into predictive systems to ensure effective risk mitigation, as supported by cross-sectional studies on vulnerability [29], [44].

Drawing on the sectoral synthesis, practical adoption should couple sensing with organizational controls: structured work-rest regimens, shaded/conditioned recovery areas, hydration protocols, and task rotation calibrated to metabolic rate and PPE burden. Index selection can follow a decision pathway: WBGT for dry, temperate settings with moderate radiation; UTCI or hybrid indices when solar load and wind effects are material; and HSI/TWL, where evaporative limitation is dominant, each paired with sector-

specific alert thresholds to reduce false positives/negatives. From a systems perspective, interoperable data schemas and open protocols are pivotal; without standard message formats and device profiles, multi-vendor integration and cross-site learning remain constrained. Data governance and privacy-preserving analytics (e.g., federated approaches) are recommended to enable model updates across sites while respecting worker privacy and regulatory requirements. Equity and cost considerations are central in low-resource settings; low-cost, ruggedized wearables, offline-capable edge analytics, and simplified dashboards for supervisors can improve feasibility without sacrificing safety performance.

As summarized in Table XI, a sector-level technology validation roadmap is provided for operational use. The roadmap organizes actions by sector and time horizon to translate evidence into deployment steps. Near-term actions prioritize open data schemas, context-contingent index selection (WBGT/UTCI/HSI/TWL), short field pilots, and organizational controls (work-rest cycles, hydration, shaded recovery areas). Mid-term actions emphasize multi-site longitudinal evaluations, multi-vendor interoperability, edge analytics for low-connectivity sites, and simplified supervisory dashboards. Longer-term actions focus on hybrid index calibration by sector and climate, privacy-preserving learning across sites, and personalized alerts that integrate workload, PPE burden, and acclimatization.

D. Strengths and Limitations

Two key strengths define this review. First, the systematic classification of the literature into seven well-defined sectors enabled the precise identification of sector-specific challenges and opportunities for technology transfer, such as applying validated mining ventilation strategies in confined indoor environments. Second, by incorporating cross-sectoral and early-stage innovations under the “Other / Unspecified” category, this study provides a broad foundation for future field validation and sectoral adaptation. However, limitations include the time window, which may have excluded emerging innovations in preprint or patent stages, and the restriction to English-language articles, potentially underrepresenting regional advances.

TABLE XI. SECTOR-TIME HORIZON ROADMAP FOR DEPLOYING OCCUPATIONAL HEAT STRESS SYSTEMS

Sector	Near-term (0–6 mo)	Mid-term (6–24 mo)	Long-term (24+ mo)
Industrial	Open data schemas; context-based index (WBGT/HSI/TWL); short field pilots; work rest	Multi-site longitudinal studies, interoperability (multi-vendor), edge analytics, dashboards & training	Hybrid index calibration by plant, privacy-preserving learning, personalized alerts, and cost-effectiveness
Construction	Standardize data; context index (WBGT/UTCI); pilots on active sites; shaded recovery	Longitudinal deployments across projects; interoperability; edge analytics; supervisor dashboards	Hybrid indices incl. wind/solar; federated learning across projects; personalized alerts by task & PPE
Outdoor	Microclimate mapping; context index (WBGT/UTCI); pilots during peak heat; work rest/hydration stations	Multi-site longitudinal seasons, interoperability, and offline edge analytics in low connectivity	Hybrid index calibration incl. radiation; privacy-preserving updates; personalized alerts by workload
Mining	Tunnel-adjusted WBGT; ventilation zoning; pilots in critical headings; recovery areas.	Longitudinal deployments, gas-safe interoperability, and edge analytics for underground networks	Sector-specific hybrid indices; privacy-preserving learning; alerts integrating PPE & acclimatization
Agriculture	Low-cost rugged wearables; crop-microclimate index (WBGT/UTCI); pilots	Longitudinal multi-farm deployments; interoperability; offline edge analytics; simple dashboards	Hybrid indices by crop/region; privacy-preserving learning; personalized alerts
Indoor	Open schemas; process-based index (HSI/TWL/WBGT); pilots; ventilation & rest areas	Longitudinal across lines/shifts, interoperability, edge analytics, and operator dashboards/training	Hybrid indices by enclosure; privacy-preserving learning; personalized alerts; implementation studies

Additionally, due to high variability in metrics, methodologies, and devices, the review did not perform a quantitative meta-analysis. Potential publication bias, geographic skew (with a concentration of studies in high-income or infrastructure-rich regions), and sponsor/funding influences on topic selection are acknowledged and should temper generalization of sectoral percentages. Mitigation steps implemented in the review included dual independent screening with adjudication, inter-rater agreement targets, harmonized search strategies with pilot/sensitivity checks, and explicit validation categories; nevertheless, translation of lab-only and pilot findings to cycle-long operations remains a critical evidence gap that future studies should prioritize through multi-site, longitudinal, and context-aware designs.

VI. CONCLUSION

This review provides a sector-specific comparative synthesis of 96 scientific articles on intelligent systems for predicting and mitigating occupational heat stress. The evidence confirms the predominance of multiparameter wearables integrated with IoT platforms and the widespread use of WBGT as a baseline screening metric, alongside increasing adoption of alternative indices (e.g., UTCI, HSI, TWL) in contexts where solar load, wind, or evaporative constraints materially affect risk. Cross-sectoral gaps persist in several key areas, including longitudinal validation under operational conditions, interoperability across devices and platforms, and the personalization of alerts to account for factors such as hydration, acclimatization, workload, and PPE burden. This review advances the field by articulating a theory-informed, sector-specific framework that links sensing modalities, validation maturity, and organizational controls, clarifying when and why particular indices and technologies are more likely to succeed in practice.

From an applied standpoint, continuous monitoring coupled with context-aware indices can support timely decisions on work-rest cycles, hydration, recovery areas, and task rotation, particularly in industrial, construction, and outdoor settings that dominate current evidence. In contrast, mining, agriculture, and indoor environments remain underrepresented in cycle-long deployments, limiting generalizability. Priority should be given to agriculture and mining, where high thermal exposure coincides with limited longitudinal evidence and infrastructural constraints that challenge real-world scale-up. Scalability and sustainability depend not only on device performance but also on interoperable data schemas, governance, and privacy safeguards, as well as total cost of ownership considerations that are pivotal in low-resource environments. Stakeholder engagement, including workers, supervisors, unions, and regulators, should be embedded from design to deployment to enhance compliance, ethical acceptability, and policy alignment.

Limitations include methodological heterogeneity that precluded quantitative meta-analysis, restriction to English-language publications, and a time window that may have excluded emergent preprints or patents. Potential publication and funding-source influences, as well as geographic skew toward infrastructure-rich regions, should temper overgeneralization of sectoral proportions and

performance claims despite the mitigation steps implemented in this review.

Future research should prioritize interoperable open data with privacy-preserving model updates; multi-site, cycle-long field deployments first in agriculture and mining; calibration of hybrid indices and sector-specific alert thresholds by climate and task; and implementation/economic evaluations that quantify feasibility, fidelity, and equity impacts. In the near term, organizations can pair context-contingent index selection with structured work-rest, hydration, and recovery protocols, and simplified supervisory dashboards; mid- and longer-term priorities include multi-site longitudinal deployments, interoperability testing at scale, and calibration of hybrid indices by sector and climate.

REFERENCES

- [1] B. F. Dehaghi, M. Amini, H. A. Rangkooy, and L. I. Ghavamabadi, "Estimation of farmworkers' exposure to heat extremes in upcoming years in the southern part of Iran," *Air Quality, Atmosphere & Health*, vol. 15, no. 8, pp. 1489-1495, Apr. 2022.
- [2] M. M. Sugg *et al.*, "Individually experienced heat index in a coastal Southeastern US city among an occupationally exposed population," *International Journal of Biometeorology*, vol. 66, no. 8, pp. 1665-1681, 2022.
- [3] H. Kim *et al.*, "Outdoor worker stress monitoring electronics with nanofabric radiative cooler-based thermal management," *Advanced Healthcare Materials*, vol. 12, no. 28, p. 2301104, Aug. 2023.
- [4] A. U. Abidin, A. L. Munawaroh, A. Rosinta, and A. T. Sulistiyani, "Heat Stress in landfill environments: Evaluating worker exposure and occupational risks," *Case Studies in Chemical and Environmental Engineering*, vol. 11, p. 101097, Jun. 2025.
- [5] H. Z. ul Hassan, A. Wang, and G. Mohi-ud-din, "A wireless sensor network for coal mine safety powered by modified localization algorithm," *Heliyon*, vol. 11, no. 1, Dec. 2024.
- [6] T. Shimazaki, D. Anzai, K. Watanabe, A. Nakajima, M. Fukuda, and S. Ata, "Heat stroke prevention in a hot specific occupational environment enhanced by supervised machine learning with personalized vital signs," *Sensors*, vol. 22, no. 1, p. 395, 2022.
- [7] À. Aduna-Sánchez, A. Correcher, D. Alfonso-Solar, and C. Vargas-Salgado, "Measuring heat stress for human health in cities: A low-cost prototype tested in a district of Valencia, Spain," *Sensors*, vol. 23, no. 22, p. 9285, 2023.
- [8] Y. S. Kim *et al.*, "Soft wireless bioelectronics designed for real-time, continuous health monitoring of farmworkers," *Advanced Healthcare Materials*, vol. 11, no. 13, p. e2200170, 2022.
- [9] C. G. Vázquez, M. Fujs, M. F. Koller, P. Wolf, and G. Da Poian, "Beat the heat: Wearable-based study of perceived heat stress and physiological strain in Swiss track workers in a controlled climate chamber," *Physiological Measurement*, vol. 45, no. 12, 2024.
- [10] T. Isaac, S. Ranjith, P. K. Latha, R. Shanmugam, and V. Venugopal, "Physiological strain in outdoor workers: The hidden danger of high humidity," *Environmental Research*, vol. 276, p. 121495, 2025.
- [11] K. K. Sarker *et al.*, "Sensor-driven automated shed and irrigation for summer tomato (*Solanum lycopersicum* L.) production in Bangladesh under the changing climate," *Results in Engineering*, vol. 15, p. 104993, Apr. 2025.
- [12] A. J. E. Bach *et al.*, "Practical cooling interventions for preventing heat strain in indoor factory workers in Thailand," *American Journal of Industrial Medicine*, vol. 67, no. 6, pp. 556-561, 2024.
- [13] I. M. Nurhartonosuro *et al.*, "Predictive model for heat stress-related symptoms among steel mill workers in East Java, Indonesia," *Malaysian Journal of Medicine and Health Sciences*, vol. 19, 2023.
- [14] R. Dwivedi *et al.*, "Granite porosity prediction under varied thermal conditions using machine learning models," *Earth Science Informatics*, vol. 18, no. 2, Jan. 2025.

- [15] K. Kato *et al.*, "Evaluating heat stress in occupational settings with no established safety standards using collective data from wearable biosensors," *Sensors*, no. 6, p. 1832, 2025.
- [16] Z. E. Petropoulos *et al.*, "Heat stress and heat strain among outdoor workers in El Salvador and Nicaragua," *Journal of Exposure Science & Environmental Epidemiology*, vol. 33, no. 4, pp. 622-630, Apr. 2023.
- [17] C. Farnham, J. Yuan, and K. Emura, "Evaluation of the cooling effect of an outdoor misting fan for workers in hot environments wearing personal protective equipment (PPE)," *Clean Technologies*, vol. 7, no. 1, p. 9, 2025.
- [18] R. Wibowo *et al.*, "Effects of heat and personal protective equipment on thermal strain in healthcare workers: Part B - application of wearable sensors to observe heat strain among healthcare workers under controlled conditions," *International Archives of Occupational and Environmental Health*, vol. 97, no. 1, pp. 35-43, 2024.
- [19] M.-Y. Cheng, Q.-T. Vu, and R.-K. Teng, "Real-time risk assessment of multi-parameter induced fall accidents at construction sites," *Automation in Construction*, vol. 162, p. 105409, Jun. 2024.
- [20] R. Ding *et al.*, "Effectiveness of a multifaceted intervention (TEMP) for prevention of occupational heat-related illness among outdoor workers in the power grid industry: A cluster randomized controlled trial," *Environ. Health Perspect.*, vol. 133, no. 1, p. 17001, 2025.
- [21] Y. Gautam and H. Jebelli, "Autoencoder-based Photoplethysmography (PPG) signal reliability enhancement in construction health monitoring," *Autom. Constr.*, vol. 165, p. 105537, Sep. 2024.
- [22] F. H. Ridwan, S. M. Anua, B. S. Aji, R. Nurdin, M. H. Rizky, and M. Tejamaya, "Assessment of occupational heat stress in a selected Indonesian steel mill," *International Journal of Occupational Safety and Health (IJOSH)*, vol. 12, no. 2, pp. 292-303, Aug. 2023.
- [23] S. A. Lewandowski and J. L. Shaman, "Heat stress morbidity among US military personnel: Daily exposure and lagged response (1998-2019)," *International Journal of Biometeorology*, vol. 66, no. 6, pp. 1199-1208, 2022.
- [24] M. A. Idris, C. Markham, K. D. Mena, and W. B. Perkison, "Examining management and employees' perceptions of occupational heat exposure and the effectiveness of a heat stress prevention intervention on safety and well-being among natural gas construction workers: A qualitative field-based study," *International Journal of Environmental Research and Public Health*, vol. 21, no. 9, p. 1255, 2024.
- [25] S. Karthick, S. Kermanshachi, and A. Pamidimukkala, "Analysis of the health and safety challenges faced by construction workers in extreme hot weather conditions," *Journal of Legal Affairs and Dispute Resolution in Engineering and Construction*, vol. 15, no. 1, Feb. 2023.
- [26] G. Ionita *et al.*, "Development of a prototype observatory of heat-related occupational illnesses and injuries through the collection of information from the Italian press, as part of the WORKCLIMATE project," *International Journal of Environmental Research and Public Health*, vol. 20, no. 5, p. 4530, 2023.
- [27] M. Sharma, N. M. Suri, S. Kant, and M. S. Alam, "Analyzing environmental heat stress under changing work conditions: A sensor-based monitoring solution," *Human Factors and Ergonomics in Manufacturing & Service Industries*, vol. 32, no. 5, pp. 389-405, Jun. 2022.
- [28] J. M. Flintoff *et al.*, "Predictive biomarkers of performance under stress: A two-phase study protocol to develop a wearable monitoring system," *BMJ Open Sport & Exercise Medicine*, vol. 11, no. 1, p. e002410, 2025.
- [29] L. G. Ioannou *et al.*, "Migrants from low-income countries have higher heat-health risk profiles compared to native workers in agriculture," *J. Immigr. Minor. Health*, vol. 25, no. 4, pp. 816-823, 2023.
- [30] A. Delgado, R. Condori, M. Hernández, E. Lee Huamani, and L. Andrade-Arenas, "Artificial intelligence model based on grey clustering to assess quality of industrial hygiene: A case study in Peru," *Computation*, vol. 11, no. 3, p. 51, 2023.
- [31] F. K. O'Connor, R. D. Meade, S. R. Notley, L. G. Ioannou, A. D. Flouris, and G. P. Kenny, "Agreement between measured and self-reported physiological strain in males and females during simulated occupational heat stress," *American Journal of Industrial Medicine*, vol. 67, no. 5, pp. 466-473, 2024.
- [32] L. Shang *et al.*, "Time and environmental conditions for heat stress recovery based on human physiological responses: Developing a predictive model," *Building and Environment*, vol. 267, p. 112228, Oct. 2024.
- [33] B. Angol, S. Sousan, and J. A. G. Balanay, "Comparison between WBGT app prototype and WBGT monitor to assess heat stress risk in an eastern North Carolina outdoor setting," *Journal of Occupational and Environmental Hygiene*, vol. 22, no. 4, pp. 274-287, 2025.
- [34] Y. Shin *et al.*, "Impact of heat stress on individual cognitive states: Utilizing EEG metrics in immersive VR-based construction safety training," *J. Manag. Eng.*, vol. 40, no. 6, Nov. 2024.
- [35] R. Kawakami *et al.*, "Cooler break areas: Reducing heat stress among construction workers in Japan," *Building and Environment*, vol. 262, p. 111821, Aug. 2024.
- [36] D. P. Bitencourt, P. A. Maia, Á. C. Ruas, and I. d. Â. d. Cunha, "Outdoor work: past, present, and future on occupational heat exposure," *Revista Brasileira de Saúde Ocupacional*, vol. 48, 2023.
- [37] V. How, S. Singh, T. Dang, L. F. Lee, and H. R. Guo, "The effects of heat exposure on tropical farm workers in Malaysia: six-month physiological health monitoring," *International Journal of Environmental Health Research*, vol. 33, no. 4, pp. 413-429, 2023.
- [38] G. Maroli *et al.*, "Wearable, battery-free, wireless multiplexed printed sensors for heat stroke prevention with mussel-inspired bio-adhesive membranes," *Biosens. Bioelectron.*, vol. 260, p. 116421, 2024.
- [39] D. B. Prasetyo, Y. Setyaningsih, Suhartono, and Suroto, "Individual, habits, and work environment factors associated with blood lactic acid levels in roof tile manufacturing workers," *Malaysian Journal of Public Health Medicine*, vol. 23, no. 1, pp. 253-260, 2023.
- [40] D. Kwaro *et al.*, "Acceptability and feasibility of research-grade wearables for monitoring heat stress in Kenyan farmers," *NPJ Digital Medicine*, vol. 8, no. 1, p. 255, 2025.
- [41] N. López-Gálvez, R. Wagoner, R. A. Canales, K. Ernst, J. L. Burgess, J. de Zapien, C. Rosales, and P. Beamer, "Longitudinal assessment of kidney function in migrant farm workers," *Environmental Research*, vol. 202, p. 111686, 2021.
- [42] W. Yi and A. P. C. Chan, "Effects of heat stress on construction labor productivity in Hong Kong: A case study of rebar workers," *International Journal of Environmental Research and Public Health*, vol. 14, no. 9, p. 1055, 2017.
- [43] M. Sharma, S. Alam, N. M. Suri, and S. Kant, "Occupational heat stress under high-heat furnace work environments - a comprehensive review on developing countries," *Journal of Thermal Engineering*, vol. 7, no. 14, pp. 2068-2092, Dec. 2021.
- [44] C. K. Uejio *et al.*, "Occupational heat exposure among municipal workers," *International Archives of Occupational and Environmental Health*, vol. 91, no. 6, pp. 705-715, Jun. 2018.
- [45] A. Bello, Y. Xue, R. Gore, S. Woskie, and D. Bello, "Exposures and urinary biomonitoring of aliphatic isocyanates in construction metal structure coating," *International Journal of Hygiene and Environmental Health*, vol. 226, p. 113495, 2020.
- [46] E. Austin, E. Kasner, E. Seto, and J. Spector, "Combined burden of heat and particulate matter air quality in WA agriculture," *Journal of Agromedicine*, vol. 26, no. 1, pp. 18-27, 2021.
- [47] S. Shakerian *et al.*, "Assessing occupational risk of heat stress at construction: A worker-centric wearable sensor-based approach," *Safety Science*, vol. 142, p. 105395, Oct. 2021.
- [48] D. P. Bitencourt, P. A. Maia, and R. C. Roscani, "The heat exposure risk to outdoor workers in Brazil," *Archives of Environmental & Occupational Health*, vol. 75, no. 5, pp. 281-288, 2020.
- [49] A. C. Kulkarni and K. Srinivasan, "Evaluation of heat stress in construction site of the metro rail in Chennai," *Indian J. Occup. Environ. Med.*, vol. 22, no. 2, pp. 101-105, 2018.
- [50] F. R. d'Ambrosio Alfano *et al.*, "Heat stress assessment in artistic glass units," *Industrial Health*, vol. 56, no. 2, pp. 171-184, 2018.
- [51] S. M. Spook, W. Koolhaas, U. Bültmann, and S. Brouwer, "Implementing sensor technology applications for workplace health promotion: A needs assessment among workers with physically demanding work," *BMC Public Health*, vol. 19, no. 1, p. 1100, 2019.
- [52] N. Beck, J. A. G. Balanay, and T. Johnson, "Assessment of occupational exposure to heat stress and solar ultraviolet radiation among groundskeepers in an eastern North Carolina university setting," *Journal of Occupational and Environmental Hygiene*, vol. 15, no. 2, pp. 105-116, 2018.

- [53] G. Legault, A. Clement, G. P. Kenny, S. Hardcastle, and N. Keller, "Cognitive consequences of sleep deprivation, shiftwork, and heat exposure for underground miners," *Applied Ergonomics*, vol. 58, pp. 144-150, 2017.
- [54] I. Vasmatazidis, R. E. Schlegel, and P. A. Hancock, "An investigation of heat stress effects on time-sharing performance," *Ergonomics*, vol. 45, no. 3, pp. 218-239, 2002.
- [55] T. D. Gibbons *et al.*, "Global REACH 2018: The influence of acute and chronic hypoxia on cerebral haemodynamics and related functional outcomes during cold and heat stress," *The Journal of Physiology*, vol. 598, no. 2, pp. 265-284, 2020.
- [56] B. N. Dang and C. H. Dowell, "Factors associated with heat strain among workers at an aluminum smelter in Texas," *Journal of Occupational and Environmental Medicine*, vol. 56, no. 3, pp. 313-318, 2014.
- [57] A. Mani, M. Rao, K. James, and A. Bhattacharya, "Individualized prediction of heat stress in firefighters: A data-driven approach using classification and regression trees," *Journal of Occupational and Environmental Hygiene*, vol. 12, no. 12, pp. 845-854, 2015.
- [58] O. Giahhi, E. Darvishi, M. Aliabadi, and J. Khoubi, "The efficacy of radiant heat controls on workers' heat stress around the blast furnace of a steel industry," *Work*, vol. 53, no. 2, pp. 293-298, 2015.
- [59] D. Tharr, "Case studies: A heat stress assessment at a Portland cement manufacturer," *Applied Occupational and Environmental Hygiene*, vol. 7, no. 7, pp. 415-417, 1992.
- [60] P. Pancardo, F. D. Acosta, J. A. Hernández-Nolasco, M. A. Wister, and D. López-de-Ipiña, "Real-time personalized monitoring to estimate occupational heat stress in ambient assisted working," *Sensors*, vol. 15, no. 7, pp. 16956-16980, 2015.
- [61] D. Tharr, "Case studies: Personal heat stress monitoring," *Appl. Occup. Environ. Hyg.*, vol. 7, no. 9, pp. 567-571, 1992.
- [62] M. J. Bird, D. L. MacIntosh, and P. L. Williams, "Occupational exposures during routine activities in coal-fueled power plants," *Journal of Occupational and Environmental Hygiene*, vol. 1, no. 6, pp. 403-413, 2004.
- [63] D. J. Brake and G. P. Bates, "Fatigue in industrial workers under thermal stress on extended shift lengths," *Occupational Medicine*, vol. 51, no. 7, pp. 456-463, 2001.
- [64] M. C. Bernhard, S. T. Kent, M. E. Sloan, M. B. Evans, L. A. McClure, and J. M. Gohlke, "Measuring personal heat exposure in an urban and rural environment," *Environmental Research*, vol. 137, pp. 410-418, 2015.
- [65] A. P. Chan and Y. Yang, "Practical on-site measurement of heat strain with the use of a perceptual strain index," *Int. Arch. Occup. Environ. Health*, vol. 89, no. 2, pp. 299-306, 2016.
- [66] H. O. Ahmed, J. A. Bindekhai, M. I. Alshuweih, M. A. Yunis, and N. R. Matar, "Assessment of thermal exposure level among construction workers in UAE using WBGT, HSI, and TWL indices," *Industrial Health*, vol. 58, no. 2, pp. 170-181, 2020.
- [67] A. Ryan and D. S. Euler, "Heat stress management in underground mines," *International Journal of Mining Science and Technology*, vol. 27, no. 4, pp. 651-655, Jul. 2017.
- [68] S. Chowdhury, Y. Hamada, and K. S. Ahmed, "Prediction and comparison of monthly indoor heat stress (WBGT and PHS) for RMG production spaces in Dhaka, Bangladesh," *Sustainable Cities and Society*, vol. 29, pp. 41-57, Feb. 2017.
- [69] M. Morabito *et al.*, "An occupational heat-health warning system for Europe: The HEAT-SHIELD platform," *International Journal of Environmental Research and Public Health*, vol. 16, no. 16, p. 2890, 2019.
- [70] J. Park and J. Kim, "Defining heatwave thresholds using an inductive machine learning approach," *PLOS ONE*, vol. 13, no. 11, p. e0206872, 2018.
- [71] S. Wang *et al.*, "Estimating occupational heat exposure from personal sampling of public works employees in Birmingham, Alabama," *J. Occup. Environ. Med.*, vol. 61, no. 6, pp. 518-524, 2019.
- [72] E. R. Watkins *et al.*, "A new occupational heat tolerance test: A feasibility study," *J. Therm. Biol.*, vol. 78, pp. 42-50, 2018.
- [73] P. Kumar, R. L. Eriksen, I. Simko, and B. Mou, "Molecular mapping of water-stress responsive genomic loci in lettuce (*Lactuca spp.*) using kinetics chlorophyll fluorescence, hyperspectral imaging and machine learning," *Front. Genet.*, vol. 12, p. 634554, 2021.
- [74] D. Shindell *et al.*, "Temporal and spatial distribution of health, labor, and crop benefits of climate change mitigation in the United States," *Proc. Natl. Acad. Sci. U.S.A.*, vol. 118, no. 46, p. e2104061118, 2021.
- [75] K. K. Zander, S. A. Moss, and S. T. Garnett, "Drivers of self-reported heat stress in the Australian labour force," *Environ. Res.*, vol. 152, pp. 272-279, 2017.
- [76] X. P. Garzón-Villalba, Y. Wu, C. D. Ashley, and T. E. Bernard, "Ability to discriminate between sustainable and unsustainable heat stress exposures Part 1: WBGT exposure limits," *Ann. Work Expo. Health*, vol. 61, no. 6, pp. 611-620, 2017.
- [77] H. Togo and A. Hirata, "Novel health risk alert system for occupational safety in hot environments," *IEEE Pulse*, vol. 12, no. 4, pp. 24-27, 2021.
- [78] R. Gun, "Deaths in Australia from work-related heat stress, 2000-2015," *Int. J. Environ. Res. Public Health*, vol. 16, no. 19, p. 3601, 2019.
- [79] K. Yeoman *et al.*, "Patterns of heat strain among a sample of US underground miners," *J. Occup. Environ. Med.*, vol. 61, no. 3, pp. 212-218, 2019.
- [80] J. Majumder, B. S. Bagepally, P. Shah, S. Kotadiya, S. Yadav, and N. Naha, "Comparison of workers' perceptions toward work climate and health symptoms between ceramic and iron foundry workers," *Indian J. Occup. Environ. Med.*, vol. 20, no. 1, pp. 48-53, 2016.
- [81] T. M. Seeberg, A.-S. B. Vardøy, M. M. V. Taklo, and H. O. Austad, "Decision support for subjects exposed to heat stress," *IEEE J. Biomed. Health Inform.*, vol. 17, no. 2, pp. 402-410, Mar. 2013, doi: 10.1109/JBHI.2013.2245141.
- [82] S. Mortazavi, M. Maracy, H. Dehghan, M. Jafari, and M. Jahangiri, "The evaluation of heat stress through monitoring environmental factors and physiological responses in melting and casting industries workers," *Int. J. Environ. Health Eng.*, vol. 1, no. 1, p. 21, 2012.
- [83] O. Delgado Cortez, "Heat stress assessment among workers in a Nicaraguan sugarcane farm," *Glob. Health Action*, vol. 2, 2009, Art. no. 2069.
- [84] H.-C. Gunga, M. Sandsund, R. E. Reinertsen, F. Sattler, and J. Koch, "A non-invasive device to continuously determine heat strain in humans," *J. Therm. Biol.*, vol. 33, no. 5, pp. 297-307, Jul. 2008.
- [85] M. Jehn *et al.*, "Tele-monitoring reduces exacerbation of COPD in the context of climate change—a randomized controlled trial," *Environ. Health*, vol. 12, p. 99, 2013.
- [86] T. M. Shockey, K. R. Babik, S. J. Wurzelbacher, L. L. Moore, and M. S. Bisesi, "Occupational exposure monitoring data collection, storage, and use among state-based and private workers' compensation insurers," *J. Occup. Environ. Hyg.*, vol. 15, no. 6, pp. 502-509, Mar. 2018.
- [87] T. C. Hower and K. D. Blehm, "Infrared thermometry in the measurement of heat stress in firefighters wearing protective clothing," *Appl. Occup. Environ. Hyg.*, vol. 5, no. 11, pp. 782-786, 1990.
- [88] A. M. Zakaria, K. H. Noweir, and G. El-Maghrabi, "Evaluation of occupational hazards in foundries," *J. Egypt. Public Health Assoc.*, vol. 80, no. 3-4, pp. 433-462, 2005.
- [89] M. L. Chen, C. J. Chen, W. Y. Yeh, J. W. Huang, and I. F. Mao, "Heat stress evaluation and worker fatigue in a steel plant," *AIHA J.*, vol. 64, no. 3, pp. 352-359, 2003.
- [90] T. Kakamu *et al.*, "Heat-related illness risk and associated personal and environmental factors of construction workers during work in summer," *Sci. Rep.*, vol. 11, no. 1, p. 1119, 2021.
- [91] R. Edirisinghe and L. Gunathilake, "IoT-based smart vest for heat stress management in construction," *Int. J. Constr. Manag.*, pp. 1-13, 2025, doi: 10.1080/15623599.2025.2504550
- [92] L. Krisher *et al.*, "Heat exposure, heat strain, and off-work recovery of Guatemalan sugarcane workers," *Am. J. Physiol. Regul. Integr. Comp. Physiol.*, vol. 328, no. 6, Apr. 2025.
- [93] Y. C. Yang, M. C. Wei, and S. J. Hong, "Evaluation of occupation hot exposure in industrial workplaces in a subtropical country," *Int. J. Occup. Med. Environ. Health*, vol. 30, no. 3, pp. 379-395, 2017, doi: 10.13075/ijomh.1896.00761.
- [94] V. M. Pacheco, R. V. d. Sousa, A. V. d. S. Rodrigues, E. J. d. S. Sardinha, and L. S. Martello, "Thermal imaging combined with

- predictive machine learning based model for the development of thermal stress level classifiers,” *Livest. Sci.*, vol. 241, p. 104244, Nov. 2020, doi: 10.1016/j.livsci.2020.104244.
- [95] M. Sharma, N. M. Suri, and S. Kant, “Analyzing occupational heat stress using sensor-based monitoring: a wearable approach with environmental ergonomics perspective,” *Int. J. Environ. Sci. Technol.*, vol. 19, no. 11, pp. 11421-11434, 2022, doi: 10.1007/s13762-021-03862-6.
- [96] M. Sulzer, A. Christen, and A. Matzarakis, “A Low-Cost Sensor Network for Real-Time Thermal Stress Monitoring and Communication in Occupational Contexts,” *Sensors*, vol. 22, no. 5, p. 1828, 2022, doi: 10.3390/s22051828.