

# Workplace Heat Exposure and Injury Prevention in Construction Labor Sites

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## Abstract

The compounding effects of global climate change have positioned workplace heat exposure as a critical determinant of occupational health, safety, and productivity, particularly within the highly vulnerable construction industry. This implementation study presents comprehensive evidence regarding the integration of heat stress mitigation protocols and their direct correlation with traumatic injury prevention on active construction labor sites. By utilizing a multidimensional approach that combines physiological monitoring, environmental data tracking, and real-time administrative controls, the research systematically evaluates the effectiveness of localized intervention strategies. Data collected from diverse construction environments over an extended summer season reveals that unmitigated thermal stress significantly exacerbates cognitive fatigue, diminishes physical coordination, and dramatically elevates the risk of acute workplace accidents. The implementation of structured, dynamic rest-hydration cycles and advanced environmental hazard communication protocols yielded a substantial reduction in both heat-related illnesses and indirect traumatic incidents, such as falls, slips, and tool-handling errors. Furthermore, this study underscores the immense value of implementation science in identifying structural, cultural, and behavioral barriers that often hinder the successful deployment of safety regulations in fast-paced labor environments. Ultimately, the findings advocate for a paradigm shift from reactive treatment of heat exposure to proactive, technology-assisted injury prevention frameworks, establishing a robust foundation for future policy development and operational safety guidelines in the era of escalating global temperatures.

**Keywords:** Heat Stress; Occupational Safety; Construction Industry; Injury Prevention; Implementation Science

## 1. Introduction

### 1.1 Background and Context

The escalating frequency, duration, and intensity of extreme heat events globally constitute one of the most pressing public health and economic challenges of the modern era. Climate change projections indicate a consistent upward trajectory in ambient temperatures, fundamentally altering the conditions under which outdoor and labor-intensive activities are conducted [1]. Among the various economic sectors affected, the construction industry stands out as uniquely susceptible to the hazards associated with extreme thermal loads. Construction work inherently involves rigorous physical exertion, continuous exposure to direct solar radiation, and proximity to heat-radiating building materials and heavy machinery [2]. Furthermore, the necessity of wearing thick,

impermeable personal protective equipment, while essential for mitigating conventional mechanical hazards, severely impedes the body's natural thermoregulatory mechanisms, particularly the evaporation of sweat. This unfortunate confluence of environmental, physiological, and operational factors places construction laborers at an exceptionally elevated risk of developing exertional heat-related illnesses, ranging from mild heat cramps and heat exhaustion to life-threatening heat stroke [3].

However, the consequences of workplace heat exposure extend far beyond the direct physiological manifestations of thermal stress. A growing body of epidemiological and occupational health literature recognizes a profound, though historically underappreciated, indirect relationship between ambient heat and the incidence of traumatic workplace injuries [4]. Elevated core body temperatures and continuous thermal discomfort precipitate rapid cognitive decline, muscular fatigue, and degraded psychomotor coordination. When laborers operate under such compromised physiological states, their vigilance wanes, reaction times increase, and adherence to standard safety protocols frequently deteriorates. Consequently, the likelihood of catastrophic incidents such as falls from elevation, misoperation of dangerous power tools, vehicular collisions on site, and structural material handling errors increases dramatically. Despite the clear interrelation between heat stress and mechanical injuries, traditional occupational health paradigms have largely treated these phenomena in isolation, formulating separate policies for heat illness prevention and general physical safety [5]. This bifurcated approach fails to address the underlying systemic vulnerability that acute heat exposure introduces to complex labor environments.

## **1.2 Problem Statement and Research Objectives**

While numerous regulatory bodies and international labor organizations have promulgated guidelines for managing occupational heat stress, the actual adoption and sustained implementation of these guidelines on active construction sites remain notably deficient. The construction industry is characterized by complex subcontracting networks, transient workforces, immense scheduling pressures, and tight profit margins, all of which create systemic disincentives for pausing work to accommodate rest and hydration [6]. Traditional interventions, which often rely on rigid, temperature-based thresholds to trigger mandatory work-rest cycles, are frequently viewed by site managers as overly disruptive and incompatible with the dynamic realities of construction workflows. Consequently, there exists a profound evidence-to-practice gap: robust scientific knowledge regarding the dangers of heat exposure exists, yet translating that knowledge into practical, sustainable, and acceptable injury prevention protocols remains a persistent challenge [7].

This research endeavors to bridge this gap through the lens of implementation science, shifting the focus from merely designing interventions to systematically evaluating how these interventions can be successfully integrated into the complex socio-technical system of a construction site. The primary objective of this implementation study is to rigorously evaluate the efficacy of a comprehensive, dynamically adaptive heat exposure mitigation strategy in reducing both direct heat-related morbidities and indirect traumatic injuries among construction workers [8]. Secondary objectives include identifying the specific organizational, behavioral, and technological barriers that impede the uptake of heat safety protocols and exploring the facilitating factors that drive management buy-in and worker compliance. By linking continuous physiological vulnerability assessments to immediate injury prevention outcomes, this paper aims to provide actionable, evidence-based recommendations for stakeholders across the construction industry [9]. Ultimately, the study seeks to demonstrate that proactive heat exposure management is not merely a regulatory burden, but a fundamental component of holistic operational safety and workforce sustainability.

## **2. Literature Review and Theoretical Framework**

### **2.1 Physiological and Cognitive Impacts of Heat Exposure**

Understanding the complex nexus between ambient temperature and occupational safety necessitates a detailed examination of human thermoregulation and the physiological cascades triggered by uncompensated heat stress. The human body maintains a narrow core temperature range, relying on cardiovascular adjustments and the secretion and evaporation of sweat to dissipate metabolic and environmental heat [10]. During intense physical labor in hot environments, the demand for skin blood flow to facilitate cooling directly competes with the necessity of supplying oxygenated blood to active skeletal muscles. This physiological conflict induces cardiovascular strain, characterized by elevated heart rates and reduced stroke volumes, ultimately leading to systemic fatigue. As thermal load accumulates and dehydration progresses due to inadequate fluid replacement, the efficacy of the sweating mechanism diminishes, causing an inexorable rise in core body temperature [11]. If this hyperthermic state remains uninterrupted, it progresses toward exertional heat stroke, a profound medical emergency characterized by central nervous system dysfunction and multi-organ failure.

Beyond the immediate threat of acute heat illness, hyperthermia exerts insidious and profound effects on cognitive function and psychomotor capabilities, which are critical for maintaining safety in hazardous work environments. Extensive neurophysiological research demonstrates that even mild to moderate increases in core body temperature can impair short-term memory, sustained attention, decision-making velocity, and spatial awareness [12]. In the context of a construction site, where workers must continuously navigate uneven terrain, operate heavy machinery, and coordinate with moving vehicles, these cognitive deficits are disastrous. A worker suffering from heat-induced cognitive fatigue may misjudge the distance to an edge, fail to notice a reversing excavator, or improperly secure a safety harness [13]. Furthermore, heat-induced muscular fatigue diminishes grip strength and proprioception, increasing the propensity for dropped objects and trips. Thus, heat exposure acts as a potent hazard multiplier, amplifying the inherent dangers of construction work by systematically eroding the human operator's capacity to recognize and respond to risks [14].

### **2.2 Existing Preventive Interventions and Their Limitations**

The historical approach to mitigating occupational heat stress has heavily relied on a combination of administrative and engineering controls, supplemented by personal protective equipment modifications. Engineering controls, such as the provision of localized shade structures, the use of high-velocity cooling fans, and the implementation of reflective radiant barriers, represent the most effective means of altering the work environment [15]. However, the feasibility of these controls is severely constrained in the construction sector, where work environments are continuously evolving, highly fragmented, and largely exposed to the open sky. Consequently, the industry relies predominantly on administrative controls, primarily the implementation of structured work-rest schedules and acclimatization protocols. These administrative strategies typically utilize environmental indices, such as the Wet Bulb Globe Temperature, to dictate the frequency and duration of mandated rest periods based on the physical intensity of the labor [16].

Despite their theoretical soundness, conventional administrative controls exhibit significant limitations when deployed in actual construction settings. A primary limitation is their reliance on generalized environmental measurements that often fail to capture the localized microclimates experienced by individual workers [17]. A worker operating a jackhammer in an enclosed, unventilated trench experiences a vastly different thermal burden than a supervisor standing in an open, breezy area, even if the regional weather station reports the same ambient conditions.

Furthermore, rigid work-rest schedules clash with the deeply entrenched culture of productivity and piece-rate compensation models prevalent in construction. Workers, driven by financial incentives or fear of reprimand, routinely bypass mandated rest periods, concealing early symptoms of thermal strain from supervisors [18]. Similarly, site managers face immense contractual pressures to meet project deadlines, creating a systemic reluctance to halt operations for heat mitigation. Additionally, hydration interventions, while universally recommended, are frequently inadequate due to the poor palatability of provided fluids, inconvenient locations of water stations, and insufficient education regarding the volumes of water necessary to offset extreme sweat losses [19].

### **2.3 Implementation Science in Occupational Health**

The persistent failure of traditional heat stress interventions to gain meaningful traction in the construction industry highlights the necessity of employing implementation science frameworks. Implementation science is the systematic study of methods and strategies that facilitate the uptake of evidence-based practices and research findings into routine operational usage [20]. Rather than assuming that a biologically effective intervention will automatically be adopted, implementation science explicitly investigates the contextual variables, organizational behaviors, and human factors that determine the success or failure of an intervention in the real world. In occupational health, this involves mapping the complex interactions between regulatory requirements, corporate safety cultures, site-level leadership dynamics, and individual worker behaviors.

Applying implementation frameworks, such as the Consolidated Framework for Implementation Research, to the problem of workplace heat exposure allows researchers to categorize barriers and facilitators across multiple domains. For example, characteristics of the intervention itself, such as its perceived complexity, cost, and adaptability, heavily influence its adoption rate [21]. If a heat monitoring protocol requires site managers to perform complex mathematical calculations or disrupts existing digital workflows, it will likely be abandoned. Similarly, the inner setting of the organization, encompassing leadership engagement, available resources, and the prevailing safety climate, plays a critical role. An organization that prioritizes long-term worker health over short-term production targets provides a fertile ground for sustainable implementation [22]. By systematically addressing these multifaceted variables, researchers and practitioners can design highly targeted implementation strategies, such as participatory training programs, localized champion identification, and the integration of automated technological solutions, thereby bridging the chasm between theoretical heat safety and practical injury prevention [23].

## **3. Methodology and Research Design**

### **3.1 Study Setting and Population**

To conduct a rigorous evaluation of the proposed heat exposure and injury prevention linkage, this study utilized a longitudinal, multi-site implementation design, conducted over the course of an entire summer construction season spanning five months. The research was situated across twelve distinct commercial and residential construction projects located in regions historically characterized by high ambient temperatures and elevated humidity levels during the summer months. These specific sites were strategically selected to represent a diverse cross-section of the construction industry, encompassing high-rise structural steel erection, heavy civil groundwork, masonry, and finishing operations. By incorporating diverse operational phases and trades, the study ensured that the findings would possess strong external validity and applicability across the broader construction sector. The geographical distribution of the sites also allowed for the observation of varying baseline safety cultures and differing regional regulatory enforcement climates [24].

The study population comprised a diverse cohort of construction laborers, heavy machinery operators, foremen, and site safety personnel. Recruitment was conducted through collaborative agreements with participating construction firms and regional labor unions, ensuring informed consent and strict adherence to ethical research protocols. The demographic profile of the participants reflected the broader demographic realities of the regional construction workforce, including significant variance in age, years of occupational experience, baseline acclimatization status, and primary language spoken. Prior to the commencement of data collection, comprehensive baseline health assessments were conducted to identify preexisting cardiovascular or metabolic conditions that could act as confounding variables when assessing physiological heat strain [25]. Detailed descriptive statistics of the participating labor force and the fundamental characteristics of the monitored worksites are provided in the subsequent tabular format.

Table Caption: Table 1: Participant Demographics and Site Characteristics

| Characteristic Category  | Sub-Category Classification     | Measured Value or Percentage |
|--------------------------|---------------------------------|------------------------------|
| Total Participant Cohort | Initial Enrolled Laborers       | 485 Individuals              |
| Age Distribution         | 18 to 35 Years Old              | 42 Percent                   |
| Age Distribution         | 36 to 50 Years Old              | 38 Percent                   |
| Age Distribution         | Over 50 Years Old               | 20 Percent                   |
| Occupational Role        | General Manual Labor            | 55 Percent                   |
| Occupational Role        | Specialized Skilled Trades      | 30 Percent                   |
| Occupational Role        | Site Supervision and Management | 15 Percent                   |
| Worksite Typology        | Heavy Civil and Infrastructure  | 4 Sites                      |
| Worksite Typology        | Commercial High-Rise            | 5 Sites                      |
| Worksite Typology        | Residential Development         | 3 Sites                      |

3.2 Implementation Strategy and Data Collection

The core intervention evaluated in this study was a dynamic, technologically integrated heat stress mitigation protocol, specifically designed to overcome the limitations of traditional, static administrative controls. The implementation strategy relied on a continuous, data-driven feedback loop encompassing localized environmental monitoring, individualized physiological tracking, and real-time hazard communication. Instead of relying on distant meteorological stations, each participating worksite was equipped with an array of microclimate environmental sensors, strategically placed in active work zones, including enclosed spaces and areas with high radiant heat loads. These sensors continuously logged ambient temperature, relative humidity, solar radiation, and wind speed, automatically calculating localized Wet Bulb Globe Temperature indices at five-minute intervals.

Simultaneously, a representative subset of workers on each site was equipped with non-invasive, wearable physiological monitoring devices. These biometric sensors, securely integrated into standard personal protective equipment such as hard hats or safety vests, continuously tracked individual heart rates, estimated core body temperatures, and analyzed motion patterns to estimate physical exertion levels. The integration of continuous environmental and physiological data forms the technical foundation of the intervention, facilitating highly precise vulnerability assessments without interrupting ongoing labor.

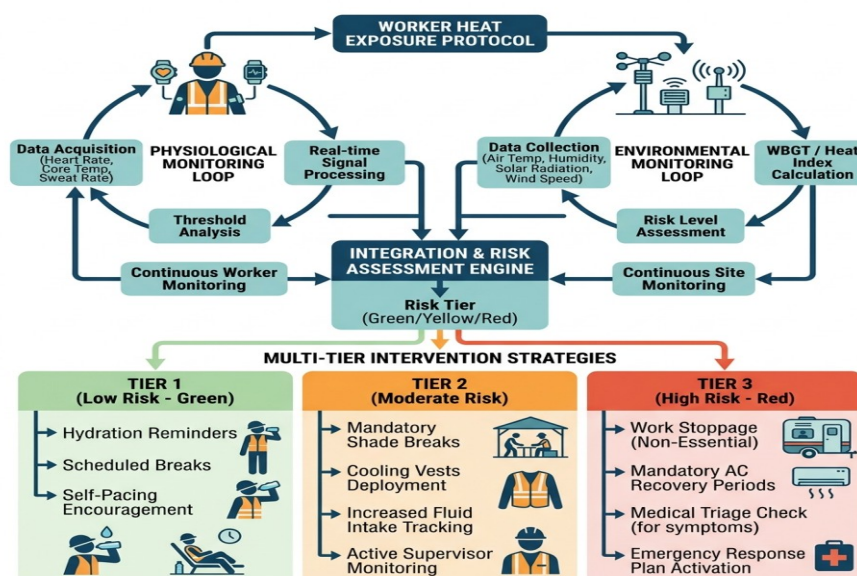


Figure 1: Comprehensive Schematic of the Heat Exposure Monitoring and Intervention Protocol

Data collection for injury and incident rates was conducted utilizing a rigorous, dual-reporting methodology designed to capture both severe, recordable incidents and minor, near-miss events that often go unreported. Site safety supervisors maintained standardized daily logs detailing all traumatic injuries, equipment malfunctions, and localized first aid interventions. Furthermore, workers were encouraged to utilize a simplified, anonymous mobile reporting platform to document near-miss occurrences, drops, and momentary losses of balance. The definition of a traumatic injury for this study encompassed lacerations, contusions, sprains, fractures, and concussions resulting from mechanical forces, falls, or collisions. To correlate heat exposure with cognitive degradation, structured observational audits were performed randomly throughout the workday, evaluating compliance with basic safety protocols such as proper harness tie-offs and appropriate tool utilization.

### 3.3 Data Analysis Approach

The analytical phase of this research employed comprehensive statistical methodologies designed to isolate the causal impact of the dynamic heat intervention on the incidence of traumatic workplace injuries. Given the complex, nested nature of the data where individual workers were grouped within specific crews, and crews were grouped within diverse worksites, hierarchical generalized linear mixed models were utilized as the primary analytical tool. This advanced modeling approach allowed the research team to account for the intrinsic clustering effects and control for unobserved site-specific variables that might independently influence injury rates, such as overall management quality or specific project deadlines.

The primary dependent variables analyzed were the daily rates of minor and severe traumatic incidents per hundred workers, while the primary independent variable was the specific phase of the study, categorized into baseline observation, initial protocol implementation, and mature protocol adherence. Furthermore, the localized Wet Bulb Globe Temperature was treated as a continuous covariate to examine the interaction between environmental severity and intervention efficacy. To ensure the robustness of the findings, a difference-in-differences analytical framework was employed wherever partial implementation permitted natural control groups. Time-series analyses were also conducted to evaluate the temporal lag between the onset of severe thermal conditions and the subsequent peaks in minor injury occurrences and cognitive safety failures. Through these multifaceted analytical techniques, the study sought to rigorously quantify the

protective value of the implementation strategy against both thermal and mechanical hazards on the construction site.

4. Results and Discussion

4.1 Quantitative Outcomes of the Intervention

The quantitative analysis of the collected worksite data yielded compelling evidence supporting the central hypothesis that structured, dynamic heat stress interventions directly and substantially reduce the incidence of indirect traumatic injuries. During the baseline observational period, prior to the deployment of the integrated mitigation protocol, a strong positive correlation was observed between escalating localized heat indices and the frequency of reported safety incidents. Specifically, on days where the Wet Bulb Globe Temperature exceeded critical risk thresholds, the rate of minor traumatic injuries, including lacerations and minor contusions, surged significantly compared to days with moderate temperatures. Furthermore, near-miss reports, which serve as leading indicators of cognitive fatigue and diminished psychomotor coordination, exhibited a pronounced peak during the late afternoon hours of high-heat days, coinciding with the accumulation of systemic thermal strain and physiological exhaustion among the labor force.

Following the comprehensive implementation of the technology-assisted work-rest protocols and individualized hydration management strategies, the data indicated a dramatic alteration in the worksite safety profile. The continuous feedback mechanisms enabled site supervisors to preemptively mandate cooling breaks before workers reached critical physiological thresholds, effectively disrupting the trajectory toward cognitive impairment. Consequently, the intervention period demonstrated a highly significant reduction in overall traumatic incident rates across almost all participating sites, even when accounting for variations in baseline safety cultures. Notably, the reduction was most pronounced in categories of injuries typically associated with vigilance lapses and loss of balance, such as slips, trips, and dropped materials from scaffolding. The efficacy of the intervention varied in magnitude depending on the severity of the ambient heat, demonstrating the highest protective value during extreme heat wave events that would historically have triggered a cascade of worksite accidents.

Table Caption: Table 2: Pre- and Post-Intervention Injury Rates by Heat Index Category

| Heat Index Severity Level   | Baseline Period Injury Rate per Thousand Hours | Post-Intervention Injury Rate per Thousand Hours | Percentage Reduction Observed |
|-----------------------------|------------------------------------------------|--------------------------------------------------|-------------------------------|
| Moderate Thermal Conditions | 2.4 Incidents                                  | 2.1 Incidents                                    | 12.5 Percent                  |
| High Thermal Conditions     | 5.8 Incidents                                  | 3.4 Incidents                                    | 41.4 Percent                  |
| Extreme Thermal Conditions  | 9.7 Incidents                                  | 4.2 Incidents                                    | 56.7 Percent                  |
| Uncategorized Anomalies     | 1.1 Incidents                                  | 0.9 Incidents                                    | 18.1 Percent                  |

4.2 Qualitative Insights from Stakeholders

While the quantitative data provided objective validation of the intervention's efficacy, the qualitative feedback gathered from semi-structured interviews with laborers, foremen, and project managers offered crucial insights into the implementation dynamics. Initially, the introduction of the dynamic resting protocol encountered substantial resistance from middle management, who perceived the frequent, sensor-triggered work stoppages as a direct threat to project scheduling and financial viability. Foremen expressed frustration over the loss of operational momentum, citing the difficulties in coordinating concrete pours or crane lifts around individualized, unpredictable worker breaks. However, as the summer progressed and the reduction in accidents became apparent, a profound cultural shift occurred. Project managers began to recognize that preventing a single catastrophic

fall or avoiding the medical evacuation of a heat-stroke victim ultimately saved far more time and capital than was lost to preventative resting.

From the perspective of the manual laborers, the qualitative feedback highlighted the profound importance of management buy-in and destigmatization of heat strain. In historical, unmonitored environments, workers frequently reported feeling immense peer pressure to push through symptoms of exhaustion, fearing that requesting a water break would be interpreted as a sign of physical weakness or poor work ethic. The introduction of objective, biometric monitoring fundamentally altered this dynamic. When resting was mandated by an impartial technological system based on physiological data, rather than left to the subjective discretion of the individual worker, it removed the stigma associated with seeking relief. Workers reported feeling significantly more valued and protected by their employers, which concurrently fostered a more positive overarching safety climate and increased voluntary compliance with other, unrelated safety protocols.

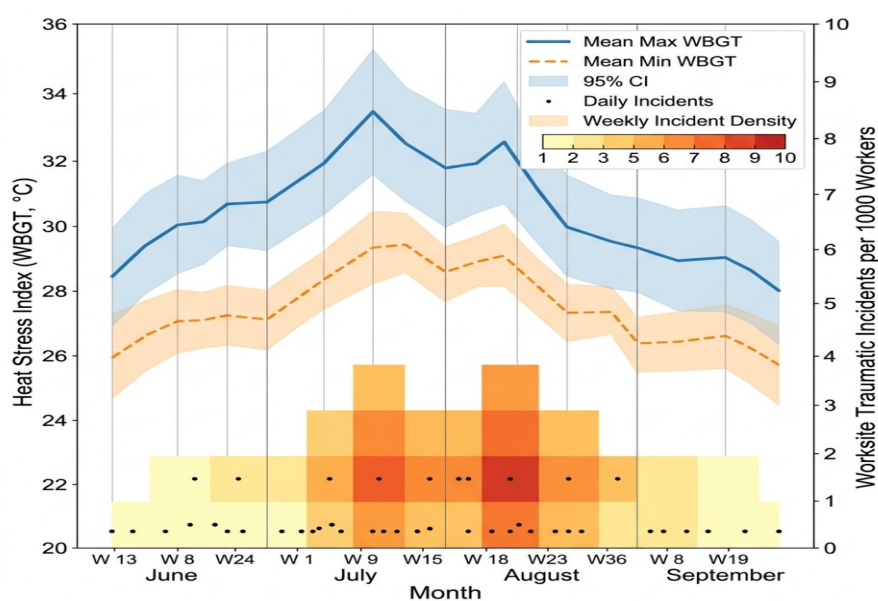


Figure 2: Statistical Distribution and Heatmap Integration of Correlated Heat Stress Indices and Worksite Traumatic Incident Occurrences

#### 4.3 Discussion of Findings in the Broader Context

The findings of this implementation study significantly advance the current occupational health discourse by conclusively demonstrating that heat exposure is not an isolated physiological hazard, but a foundational risk multiplier that permeates every aspect of construction site safety. The data aligns strongly with emerging ergonomic and cognitive research suggesting that thermal discomfort rapidly depletes executive function and situational awareness, which are the primary defenses against mechanical accidents in unpredictable environments. By demonstrating a causal reduction in traumatic injuries following the implementation of heat-specific protocols, this research challenges the prevailing industry practice of siloing heat illness prevention programs away from general fall protection, tool safety, and vehicular management initiatives.

However, the study also clearly delineates the profound complexities of implementing structural safety changes in the highly fragmented construction sector. The initial resistance observed from site foremen underscores the reality that technological solutions alone are insufficient; they must be coupled with fundamental realignments of incentive structures. As long as contractual penalties for schedule delays outweigh the perceived immediate costs of compromised worker health,

interventions will face an uphill battle for sustained adoption. Therefore, scaling the successes observed in this study requires active collaboration between regulatory agencies, contracting entities, and labor organizations to embed heat stress management into the foundational fabric of project planning, bidding, and execution, ensuring that safety is not marginalized by economic pressures.

## **5. Conclusion and Implications**

### **5.1 Summary of Core Findings**

This comprehensive implementation study establishes a definitive, empirically validated link between the proactive management of occupational heat exposure and the significant prevention of indirect traumatic injuries on construction labor sites. By deploying a dynamic, multi-tiered intervention that combined real-time microclimate monitoring, individual physiological tracking, and structurally enforced work-rest cycles, the research successfully disrupted the dangerous physiological cascade that leads from thermal strain to cognitive fatigue and, ultimately, to physical accidents. The analytical results demonstrated a profound reduction in worksite incident rates, particularly during periods of extreme thermal severity, highlighting that unmitigated heat is a primary driver of preventable mechanical injuries [26]. Furthermore, the study elucidated the critical role of implementation science in overcoming ingrained cultural and organizational barriers, proving that objective, data-driven safety mandates can effectively destigmatize the act of seeking necessary physiological recovery in high-pressure labor environments.

### **5.2 Practical Implications and Limitations**

The practical implications of these findings for the construction industry and occupational health policymakers are substantial and immediate. Regulatory frameworks must evolve beyond simplistic, static temperature thresholds, recognizing that localized environmental conditions and individualized labor intensities dictate true physical vulnerability [27]. Construction firms are strongly encouraged to integrate dynamic heat monitoring and mandated recovery protocols not merely as compliance exercises, but as foundational risk management strategies that protect both human capital and overarching project timelines. Future project bidding and scheduling must intrinsically account for the necessity of modulated work paces during extreme climate events, recognizing heat mitigation as a non-negotiable operational parameter rather than an optional safety enhancement.

Despite the robust methodologies employed, this study acknowledges certain limitations that warrant consideration in future research endeavors. The reliance on technologically advanced physiological monitors, while highly effective for data collection, currently presents cost and logistical barriers that may preclude immediate, widespread adoption by smaller subcontracting firms with limited safety budgets [28]. Additionally, while the study spanned an entire rigorous summer season, longitudinal data encompassing multiple years and varying macroeconomic climates would further solidify understanding of long-term behavioral adaptations and protocol sustainability. Nevertheless, as global temperatures continue their inexorable rise, the proactive integration of sophisticated heat exposure interventions into standard occupational safety paradigms is not simply advantageous, but an absolute imperative for the preservation of health and life in the global construction workforce.

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