

1 Article

2 Development of an IoT-based control system for real-time heat 3 stress management in the oil and gas sector

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10 Abstract

11 This study presents the design of a scalable IoT-based control system for mitigating heat
12 stress in oil and gas workers through real-time monitoring and rule-based proactive deci-
13 sion-making. The system consists of an ESP32 microcontroller with environmental
14 (DHT11), physiological (MAX30100) and motion (PIR) sensors. The data has been col-
15 lected at ambient temperature and heart rate corresponding to the activity level of the
16 worker. In contrast to traditional wearable solutions, the designed system is centrally co-
17 ordinated, collects real-time data, conducts server-side filtering and apply logical algo-
18 rithms to estimate core temperature, work intensity and heat stress index (HSI). This HSI
19 assists in determining rest periods, hydration strategies, work-rest cycles and the use of
20 cooling adjuncts through rule-based decision-making. This data is monitored by facility
21 managers to avoid heat-related incidents through proactive measures. The outcomes are
22 useful for organizations to maintain workers' health status, achieve operational efficiency
23 and meet regulatory requirements while working in extreme operating conditions.

24 **Keywords:** Cloud-based monitoring; Heat stress management; Heat stress index; IoT; Oil
25 and gas; Rule-based decision-making

27 1. Introduction

28 Globally, oil and gas industry is facing heat stress as a major threat to safety and
29 productivity of workers [1]. According to the Bureau of Labor, 479 workers in the United
30 States of America (USA) died from environmental heat exposure with an average of 40
31 fatalities annually, and 33,890 work-related heat injuries and illnesses from 2011 to 2020.
32 Heat stress is affecting 70% of the global workforce and causing nearly 19,000 deaths an-
33 nually thereby impacting vulnerable workers exposed to multiple climate-related hazards
34 [2]. By 2030, heat stress is projected to cause a global productivity loss of up to 3.8%, equiv-
35 alent to 136 million full-time jobs and \$2.4 trillion in economic losses, disproportionately
36 affecting low- and middle-income countries [3]. Previously, [Shin, et al. \[4\]](#) and [Girard, et
37 al. \[5\]](#) identified that heat exposure cause cognitive issues such as foggy attention and
38 disruption in decision-making. To overcome this issue, the traditional work-rest schemes
39 and hydration policies were found to be inflexible due to their inability to provide real-
40 time forecasting [6]. This limitation triggered the need for real-time and technology-

41 driven solution to heat stress particularly in labor intensive environments [7]. In this con-
42 text, [Paroha \[8\]](#) proposed an AI-driven cloud architecture for centralized monitoring and
43 decision making. Similarly, [Sabrin, et al. \[9\]](#) and [Varghese, et al. \[10\]](#) proposed a multi-
44 layered preventive measure plan involving hydration schedule and usage of standardized
45 indices (i.e., wet bulb globe temperature (WBGT) and heat stress index (HSI) to control
46 the risks. The predictive analytics through machine learning algorithms were also used to
47 enhance the efficiency of heat stress management frameworks [11].

48 These advancements in heat stress management led to innovative solutions across
49 various industrial sectors. For instance, [Edirisinghe and Gunathilake \[12\]](#) developed a
50 smart vest to continuously monitor workers' physiological parameters (i.e., skin temper-
51 ature and heart rate) in high temperature conditions to prevent heart-related illnesses. [Liu,
52 et al. \[13\]](#) proposed climate resilient building designs using solar-reflective roofing and
53 hybrid ventilation to reduce heat stress in dairy cattle housing. [Lim, et al. \[14\]](#) and [Patel,
54 et al. \[15\]](#) monitored real-time physiological fatigue (i.e., change in heart rate and skin
55 temperature) through IoT integrated wearable bands and safety vests. Similarly, smart
56 heating, ventilation and air conditioning (HVAC) integrated systems were used to modify
57 real-time indoor climate conditions based on sensor inputs [16]. The biosensor technolo-
58 gies are also making traction in this field. In this regard, [BinZiad, et al. \[17\]](#) proposed a
59 bio-signal patch to personalize hydration interventions by analyzing workers' sweat
60 traces and body temperature.

61 In lieu of the above discussion, numerous solutions have been proposed for heat
62 stress management, however, existing solutions rely on individual wearables (e.g., smart
63 vests and biosensor patches) [12, 17]. These solutions lack centralized control and scala-
64 bility in industrial settings. Moreover, AI-driven frameworks are theoretical and rarely
65 implemented in real-time harsh environments of oil and gas industrial operations [9, 10,
66 18]. These gaps trigger the need for a scalable IoT-based centralized control system for
67 real-time monitoring and rule-based decision-making. To address these gaps, this study
68 focuses on designing an IoT-based central control system for heat stress management in
69 the harsh environment of oil and gas industry. The system includes environmental
70 (DHT11) and physiological (MAX30100) sensors as inputs wired with a motion (PIR) sen-
71 sor, an ESP32 microcontroller and an external sensor for wireless transmission to a cloud
72 platform. Outcomes of this study enable worker safety, cognitive performance and oper-
73 ational efficiency through real-time monitoring of heat-related incidents, worker concen-
74 tration and production efficiency in extreme work conditions.

2. Materials and Methods

This study uses a structured multi-phase approach to design and validate an IoT-based control system for real-time heat stress management in the oil and gas industry. For this purpose, two data sets have been integrated into the central server system including meteorological administration data, and oil and gas sector data. Meteorological administration includes data related to heat stress index, and data related to the oil and gas sector includes workers' body temperature, heart rate, activity level, environmental temperature and environmental humidity level. After data filtration, an overall heat assessment (OHA) has been carried out to collect the baseline information. The framework used for designing this IoT-based heat stress management system is shown in Figure 1.

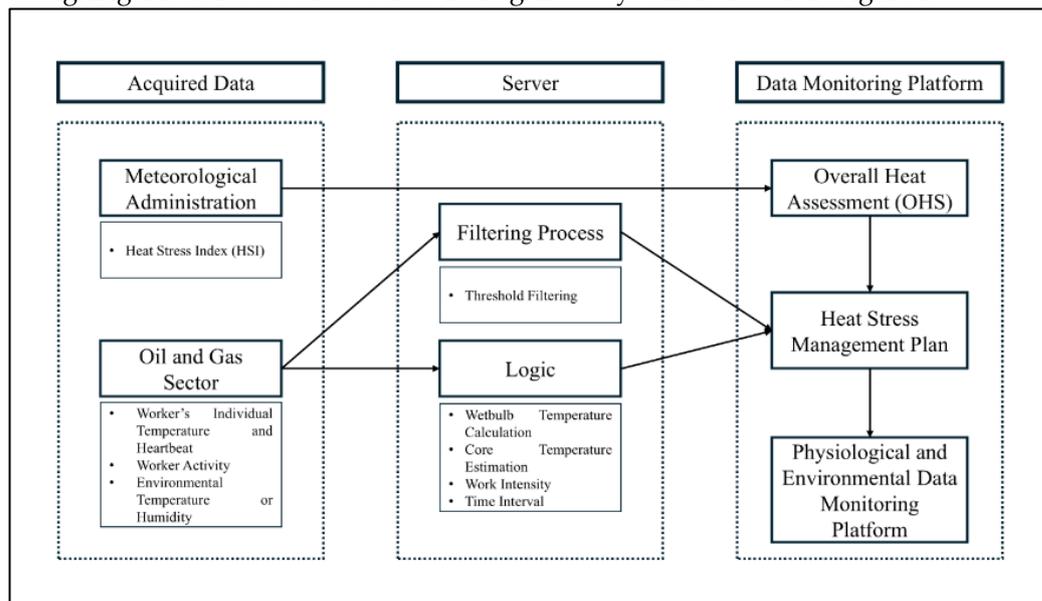


Figure 1. Framework for IoT-based heat stress management in the oil and gas sector.

Figure 1 shows that the system focuses on systematic progression from conceptualization to implementation and evaluation. The figure illustrates a centralized IoT-based system that collects real-time meteorological and worker physiological data, processes it on a server using filtering and logical algorithms, and generates heat stress assessments. These assessments support proactive heat stress management and continuous monitoring to protect oil and gas workers.

The entire design process has been segmented in distinct stages to ensure clarity, technical soundness and compliance with occupational safety standards. These stages include stakeholder analysis, feasibility study, development of heat stress management plan, system architecture design, system development and installation, compliance and regulatory consideration, validation through real-time case study, and conclusive outputs, as illustrated in Figure 2.

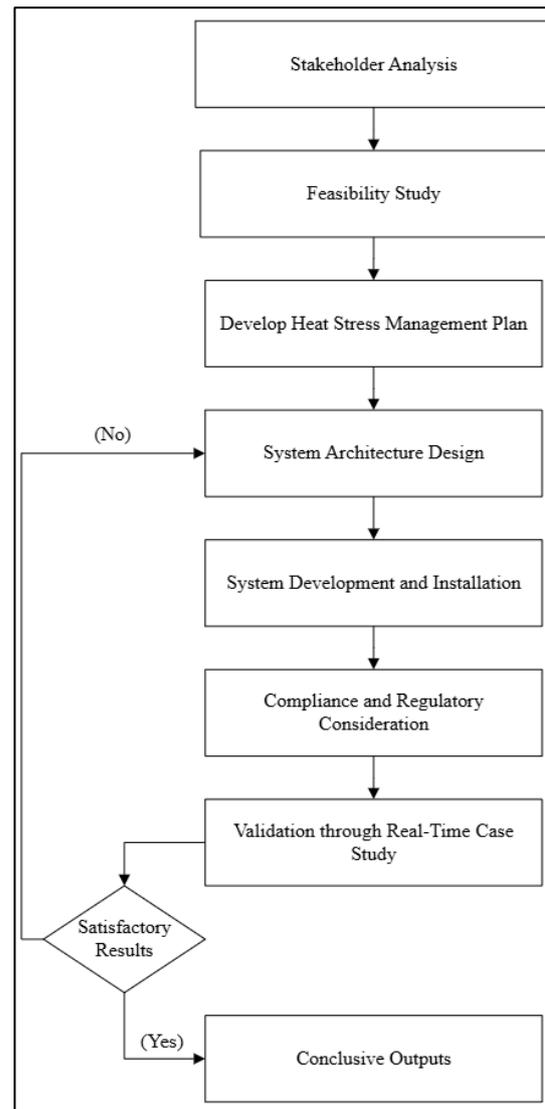


Figure 2. Sequence steps involved in the designing of proposed control system.

Figure 2 shows that the design process involves feasibility assessments, technical evaluation, stakeholder engagement and compliance reviews. Each step contributed to meeting real-time monitoring demands in industrial environments. These steps are explained below.

2.1. Stakeholder analysis

The stakeholders were identified and their needs regarding heat stress management were analyzed. These stakeholders include (i) workers operating in extreme temperature conditions, (ii) management teams implementing occupational safety standards, (iii) health, safety and environment (HSE) personnel complying with occupational safety laws, (iv) team performing installation, maintenance and audit of IoT system, and (v) other individuals (i.e., suppliers of IoT devices, legal enforcing bodies, and external auditors to ensure industrial compliance). This step assisted in refining the system based on the suggestions of stakeholders.

2.2. Feasibility study

After stakeholder analysis, a feasibility study has been carried out to determine technical, economic and operational viability of the system. This step addressed (i) technical

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feasibility based on the capability of sensors and network integration, (ii) economic feasibility based on the costs of hardware and installation, and (iii) operational feasibility by checking whether the system is easily put into practice without interruptions.

2.3. Development of heat stress management plan

A full-scale heat stress management plan has been developed to process the data received by IoT sensors in real-time, as illustrated in Figure 3. It works by connecting sensor data, weather conditions and physiological measurements into one central logic block that is used to promptly respond with safety action. This plan assists safety managers to make informed decisions about the choice and adoption of preventive and corrective measures.

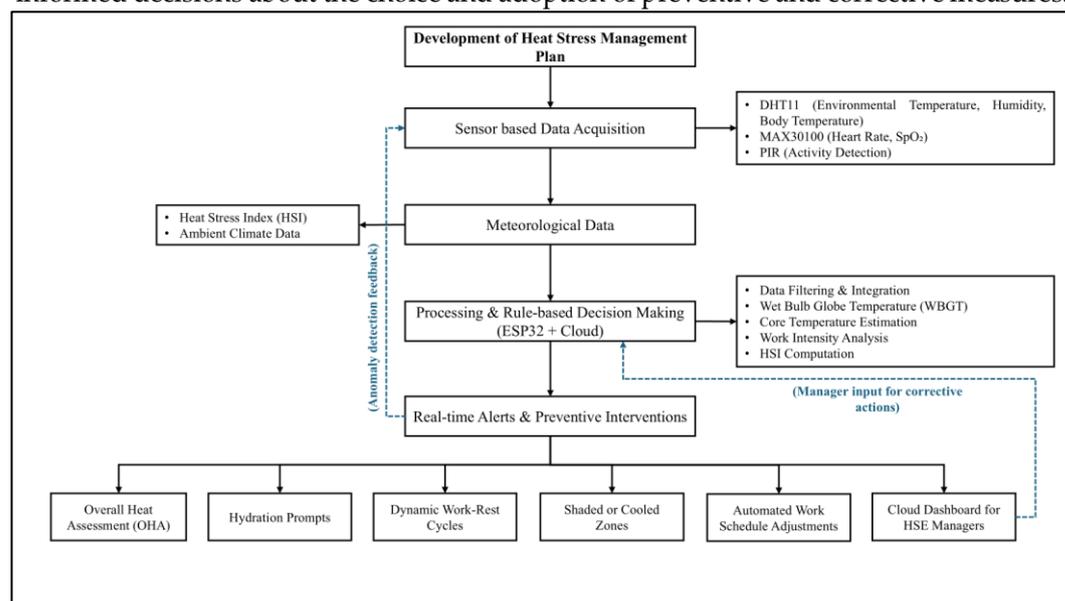


Figure 3. Framework used for the development of heat stress management plan.

The design of the developed system is presented in Figure 3. The system takes data from various IoT sensors including (i) DHT11 (environmental temperature, humidity, and body temperature), (ii) MAX30100 (heart rate and SpO₂), and (iii) PIR sensor (activity detection). This data is converted into valuable information for the calculation of heat stress index (HSI). Meteorological data is also collected for the computation of HSI and other environmental parameters. This data is transformed into a rule-based decision-making module (i.e., ESP32 and Cloud) to assimilate the input, calculate the wet bulb globe temperature (WBGT), estimate core temperature and analyze the intensity of work. The system gives real-time warnings and prevention strategies to intimate users with hydration alerts, work-rest schedules, shady or cool areas, automated work schedules, and a built-in cloud dashboard to help HSE managers.

Moreover, two feedback mechanisms have been incorporated in the framework to enhance system reliability and flexibility. First is the anomaly detection feedback, which runs in a backward mode i.e., back to the sensor-based data acquisition module using real-time alerts. To maintain accuracy, this feedback allows automatic validation of sensor data when anomalous or unusual readings are detected. Manager input on corrective actions is the second feedback mechanism which runs between the cloud dashboard and the decision-making module. Through this channel, HSE managers interpret system outputs, evaluate the situation in the field and adjust decision rules based on real-time observations or reports of an incident. These feedback mechanisms convert the structure into a closed IoT-based control mechanism, which requires continuous learning, recalibration and better decision-making for worker safety.

2.4. System architecture

This step monitors the hardware modules in real-time. For this purpose, a DHT11 sensor has been used to measure environmental temperature, humidity and worker body temperature. Similarly, a MAX30100 sensor has been deployed to collect worker health information including heart rate and peripheral capillary oxygen saturation (SpO₂) level. The central processing unit is an ESP32 microcontroller that collects and transmits sensor data to a cloud-based system through Wi-Fi. A Proximity IR (PIR) sensor has also been used to ensure energy efficiency by collecting data in the presence of a worker. The real-time local monitoring is shown by an LCD 1602 display where a secure Wi-Fi ensures strong data transmission. Along with algorithms for predictive analysis, software integration has also been used to facilitate cloud-based dashboard through centralized monitoring and rule-based decision-making. Figure 4 shows the architecture of designed system.

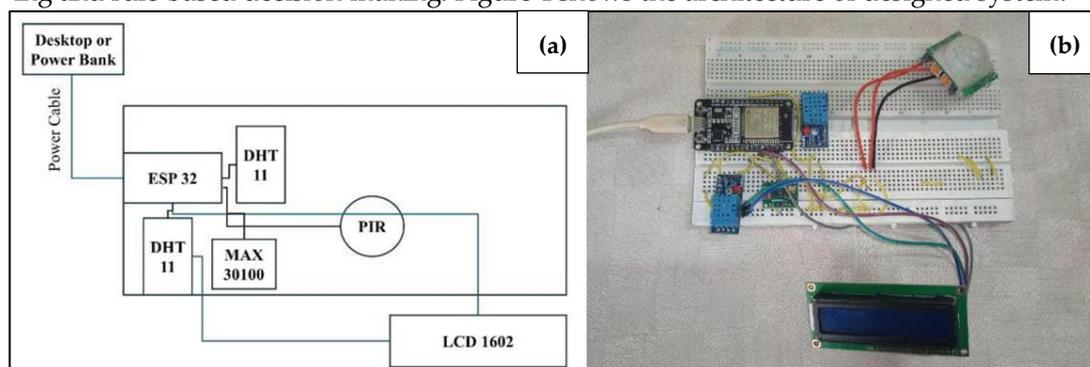


Figure 4. System architecture representing (a) information flow and (b) designed module.

2.5. System development and installation

At this step, hardware is assembled, software is programmed, and data is transmitted in real-time. The ESP32 microcontroller has been configured to process sensor input efficiently for data transmission. Additionally, cloud storage has been provided for data analysis, real-time visualization and alert generation using software interface. This network protocol ensures process stability and data transmission reliability for system installation at designated worksites.

2.6. Compliance and regulatory consideration

Once the system is installed, the emphasis is posed on compliance to minimize the violations against occupational safety and environmental regulations. For this purpose, continuous monitoring has been carried out to identify and mitigate the potential violations. During this process, ethical concerns (i.e., workers' consent encryption and secure transmission protocols) have been implemented to protect worker information.

2.7. System validation

Its efficiency has been confirmed with the help of the real-time case study during which sensor nodes were located inside a high-risk heat environment. The best working of the system was perceived using performance metrics (i.e., sensor accuracy and response time in alert). The system inefficiencies have been dealt with by the adjustments of sensor locations, data analytics, and calibration. This refinement allowed the system to be constantly improved hence lowering risks of heat stress among the workers.

3. Results

The system has been tested in a simulated setting that is of high-risk work characteristics. The most important parameters related to the environment (i.e. ambient temperature and humidity) and physiology (i.e. body temperature and pulse rate) as well as their ranges are presented in Table 1.

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Table 1. Environmental and physiological parameters measured during system validation.

Parameters	Range	Average
Ambient temperature (°C)	33.5 – 43.7	38.1
Humidity (%)	41 – 74	60.2
Body temperature (°C)	36.2 – 38.5	37.2
Pulse rate (bpm)	71 – 109	92.5

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Table 1 verifies the system as having the capability to capture real-time changes in the conditions that influence the safety of the workers. The data reveals that ambient temperature values were up to 43.7 °C, which was practically identical to severe thermal conditions that the oil and gas surroundings experience. The humidity was the highest at 74 % that is specifically unhelpful since it interferes with the natural cooling mechanism of the human body through perspiration and increases vulnerability to heat-related illnesses. Furthermore, average body temperature (37.2 °C) hovered near the upper safety threshold indicating sustained exposure to heat during the simulated tests. The average pulse rate was measured at 92.5 bpm and this showed that the workers were struggling physically or their heart rate was high and mostly when the heat detected at the peak. A combination of these observations proves the system to be capable of proper tracking of real-time physiological and environmental changes to support its significance as a valid occupational health and safety measure of extreme work environments.

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3.1. *Threshold breach analysis*

The critical condition has been determined to assess the system alert performance under thermal stress. These conditions were evaluated based on predefined safety thresholds, as shown in Table 2.

Table 2. Conditions observed under thermal stress.

Parameter	Threshold value	Condition	Frequency	Interpretation
Ambient temperature	> 40°C	Heat stress alert	2	Potential for heat stroke
Humidity	> 70%	Discomfort zone	3	Sweating ineffective
Body temperature	> 37.5°C	High-risk warning	2	Core overheating risk
Pulse rate	> 100 bpm	Cardiovascular load	5	Cardiovascular strain

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Table 2 reveals the circumstances when critical thresholds were breached because of the high body temperature and ambient temperature. It substantiates the responsiveness of the system towards the detection and signaling of unsafe working conditions. For instance, one can note the effectiveness of systems by identifying five cases of high heart rate more than 100 bpm, which is the most breached parameter and an evident sign of cardiovascular stress among workers. Equally, there are three results showing the breaching of humidity (i.e., >70%), two results of breaching of ambient temperature (i.e., >40 °C) and body temperature (i.e., >37.5 °C) as well. It is interesting to note that real-time notification was also generated in relation to these breaches that represent systems ability to detect various types of thermal threats. These results confirm high sensitivity of the system in responding in-time to interventions and proactive measures to the avoidance of heat-related incidents. Figure 5 reflects the output of system.

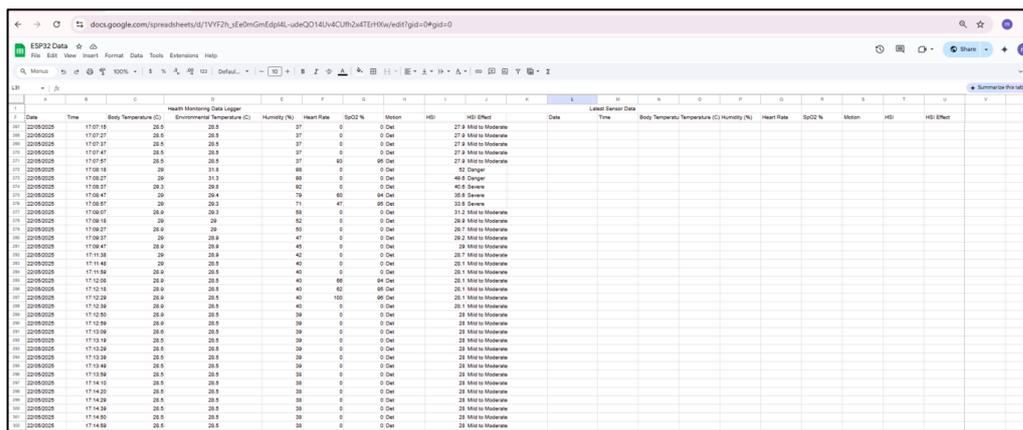


Figure 5. Real-time sensor data log from the ESP32-based IoT system.

3.2. Critical point analysis

Critical points are instances where multiple physiological and environmental thresholds are breached simultaneously, indicating an elevated risk to worker’s health. The data points out that the midday period is critical in nature since ambient temperature, humidity and pulse rate were most intense in parallel to each other hence resulting in a compounded thermal stress situation. A positive correlation between ambient temperature and heart rate showing that there is thermal strain was also confirmed by the analysis of cross-correlation. Multi-parameter decision-making capability of the system can be proven with the help of the outcomes that allow the system to identify these overlapping stress indicators effectively and provide real-time alerts. It is noteworthy that identifying these critical points is imperative to mitigate heat-related risks in high-stress environments by using dynamic work-rest cycles and deploying targeted hydration as recovery measures.

To evaluate the effectiveness of the designed heat stress management system with the help of IoT, Table 3 presents a comparison analysis with references to the major shortcomings of the already designed systems. The most popular uses of IoT within the occupational safety area were applications involving the wearable physiological information, and they were not capable of making real context decisions [12, 17]. On the other hand, the developed system ensured environmental sensors were used, motion detection using a PIR sensor, real-time dynamic notifications, and timely interventions using rule-based logic.

Table 3. Existing IoT-based heat stress monitoring systems and improvements in the developed system.

Sr. No.	Study	Limitations	Improvement in the developed system
1	Kim, et al. [19]	Focused only on wearable physiological bands	Added environmental sensors and motion detection for extensive monitoring
2	Sergi, et al. [16]	Static HVAC control with no individual-level feedback	Enabled real-time alerts based on personalized sensor data and environmental thresholds
3	Edirisinghe, et al. [20]	Limited to passive monitoring of vital signs	Integrated rule-based decision-making for proactive interventions
4	Patel [21]	Emphasized fatigue detection without heat stress-specific indices	Focused on calculating HSI and thermal risk indicators for heat-specific response
5	BinZiad, et al. [17]	Lacked centralized control or multi-sensor inputs	Developed a centralized system integrating environmental, physiological and motion data

6	Paroha [22]	No hardware implementation	Implemented a real-time system using ESP32 and IoT sensors for field deployment
7	Liu, et al. [23]	Focused on heat stress in animals and building designs, not human applications	Applied modeling logic to human monitoring with cloud-connected real-time alerts
8	Edirisinghe and Gunathilake [12]	Wearable vest limited to basic parameters and no system automation	Developed a non-wearable alternative with automated logic and scalable system integration

Table 3 reveals the weaknesses of the past research on the monitoring of heat stress. As an example, [Kim, et al. \[19\]](#) used wearable bands to monitor physiological indicators without paying attention to heat and humidity as important factors of the environment. Similarly, [Edirisinghe and Gunathilake \[12\]](#) developed a smart vest, however, lacked automation and scalability. In contrast, current study addresses the gaps of previous studies by designing a centralized IoT platform powered by an ESP32 microcontroller, and integrating environmental sensors (like DHT11), physiological sensors (MAX30100) and a motion sensor (PIR). Likewise, [Sergi, et al. \[16\]](#) concentrated on smart climate control HVAC systems that adapted the environmental conditions without considering an individual worker physiology or activity level, in addition to the real-time risk assessment of heat-stress, which restricted the areas of their implementation in dynamic outdoor oil and gas processes. Additionally, a cloud-based AI-computed language of centralized heat stress control and decision-making was suggested by [\[22\]](#), but the methodology was mostly theoretical and not connected to the hardware level and implemented in the severe industrial setting. In combination with real-time condition monitoring, this system uses rule-based decision-making, as well, to activate proactive, scalable and relevant alerts in the oil and gas industry. Essentially, the designed system integrates everything where other systems were lacking in terms of integration, flexibility and practicality, ensuring the safety of workers.

4. Discussion

This research indicates that there was a major enhancement of real-time management and detection of heat stress in oil and gas industrial environment. The executed IoT-based system incorporates several data sources (e.g., physiological, environmental and motion) (compared to the previous solutions where most solutions were wearable-only), to have a comprehensive picture of the health of a worker. This system, unlike in the past where people could only see the passive side of the monitoring process, also provides the functionality of rule-based decision programming that enables the proactive provision of intervention in the form of alerts and automatic control recommendations. As an example, [BinZiad, et al. \[17\]](#) suggested a bio-signal patch but it was not centralized and cited multi-sensors which reduced the scale and multi-responsiveness. This gap has been addressed by incorporating cloud-based decision-making linked with a centralized ESP32 microcontroller that responds dynamically to threshold breaches and validating the system through multiple recorded events in real-time data logs. Similarly, [Liu, et al. \[23\]](#) modeled for animal welfare under heat stress, however that is not directly useable for human occupational safety. To fill this gap, current study applied similar predictive concepts to human applications, delivering real-time alerts and using the HSI to assess working conditions accurately. Likewise, [Paroha \[22\]](#) suggested a centralized AI architecture for workplace safety but the implementation remained theoretical. In lieu of the above, current study implemented this framework and validated it through field-level simulation, thereby providing empirical evidence for its effectiveness. Therefore, outcomes demonstrate that in comparison to literature, the developed system uniquely integrates real-time

287 data logging, wireless transmission, intelligent alert systems and cloud-based dashboards.
288 These features make the system scalable for practical deployment and more responsive
289 than existing tools.

290 5. Practical Implications

291 The outcomes demonstrate that the developed system is effective in terms of respon-
292 siveness, reliability and provision of safety for workers. The ESP32 microcontroller profi-
293 ciently collected and transmitted data and turned on alerts when sensor measurements
294 crossed the threshold limits. The system monitors body temperature and pulse rate to
295 prevent overheating, especially regarding safety. This system has serious implications for
296 various stakeholders. As a future researcher, the system would be an empirical tool that
297 can be used to conduct future research in the areas of AI-based safety frameworks, pre-
298 dictive health analytics and reconfigurable IoT applications. For industries, it provides a
299 real-time, automated and proactive solution to monitor workers' physiological and envi-
300 ronmental parameters in compliance with occupational health and safety standards. Sim-
301 ilarly, policymakers and governments can use this system to support dynamic labor poli-
302 cies by integrating real-time heat stress into national safety regulations, particularly in
303 regions vulnerable to climate change. Furthermore, this study is consistent with the goals
304 of SDG-3 and SDG-8 since it attempts to overcome the limitations of past models and con-
305 dense centralized control along with the decision-making based on rules

306 6. Conclusions

307 This study designed and tested a real-time IoT-based control system to regulate heat
308 stress in oil and gas operations. This was made possible through environmental and phys-
309 iological sensors using centralized ESP32 microcontroller where continuous online moni-
310 toring was used and risks predicted and notified to the users according to the rules of HSI.
311 This implementation reliably recognized serious risks and promptly launched safety ac-
312 tions. The practical applicability and responsiveness of developed system make it a valu-
313 able tool for improving occupational safety in workplaces exposed to extreme thermal
314 conditions.

315 Abbreviations

316 The following abbreviations are used in this manuscript:

AI	Artificial Intelligence
bpm	Beats per Minute
DHT11	Digital Humidity and Temperature Sensor (Model 11)
ESP32	Espressif Systems 32-bit Microcontroller
HVAC	Heating, Ventilation and Air Conditioning
HSE	Health, Safety and Environment
HSI	Heat Stress Index
IoT	Internet of Things
IR	Infrared
LCD	Liquid Crystal Display
MAX30100	Pulse Oximeter and Heart Rate Sensor Module
OHA	Overall Heat Assessment
PIR	Passive Infrared Sensor
SDG	Sustainable Development Goal
SpO ₂	Peripheral Capillary Oxygen Saturation
USA	United States of America
WBGT	Wet Bulb Globe Temperature
Wi-Fi	Wireless Fidelity

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