การพัฒนาและประเมินประสิทธิภาพระบบเฝ้าระวังดัชนีความร้อนและแจ้งเตือนแบบเรียลไทม์ด้วยเทคโนโลยีอินเทอร์เน็ตของสรรพสิ่งสำหรับการฝึกทหาร: กรณีศึกษา กองพันทหารสื่อสาร กรมการสื่อสารทหาร กองบัญชาการกองทัพไทย

Development and Performance Evaluation of an IoT-Based Real-Time Heat Index Monitoring and Alert System for Military Training: A Case Study of the Signal Battalion, Directorate of Communications and Information Technology, Royal Thai Armed Forces Headquarters

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Received: June 30, 2026 **Revised:** August 5, 2026 **Accepted:** August 17, 2026

บทคัดย่อ

การเจ็บป่วยจากความร้อนเป็นความเสี่ยงสำคัญที่ส่งผลกระทบต่อความปลอดภัยและประสิทธิภาพการฝึกทหาร ขณะที่ระบบเฝ้าระวังที่ใช้อยู่ยังขาดการประเมินความเสี่ยงและการแจ้งเตือนแบบเรียลไทม์ การวิจัยนี้มีวัตถุประสงค์เพื่อ 1) พัฒนาระบบเฝ้าระวังดัชนีความร้อนและแจ้งเตือนแบบเรียลไทม์ด้วยเทคโนโลยีอินเทอร์เน็ตของสรรพสิ่ง (IoT) สำหรับการฝึกทหาร 2) ประเมินประสิทธิภาพของระบบด้านความถูกต้องของการจำแนกระดับความเสี่ยง ความน่าเชื่อถือในการรับส่งข้อมูล และระยะเวลาในการแจ้งเตือน และ 3) ประเมินความพึงพอใจของผู้ใช้งาน การวิจัยเป็นการวิจัยและพัฒนา (Research and Development: R&D) ตามวงจรการพัฒนาระบบ (System Development Life Cycle: SDLC) โดยพัฒนาระบบที่ประกอบด้วยเซนเซอร์ SHT31 ไมโครคอนโทรลเลอร์ ESP32 ฐานข้อมูล Firebase Realtime Database เว็บแดชบอร์ด และ LINE Official Account ศึกษาจากบุคลากรที่เข้ารับการฝึกวินัยกำลังพล กรมการสื่อสารทหาร กองบัญชาการกองทัพไทย จำนวน 40 นาย โดยใช้การเก็บข้อมูลจากประชากรทั้งหมด และประเมินประสิทธิภาพด้วยการทดสอบการจำแนกระดับความเสี่ยง 50 กรณี การรับส่งข้อมูล 100 ครั้ง และการวัดระยะเวลาแจ้งเตือน 10 ครั้ง ผลการวิจัยพบว่า ระบบสามารถจำแนกระดับความเสี่ยงจากความร้อนได้ถูกต้องร้อยละ 100.00 อัตราความสำเร็จในการรับส่งข้อมูลร้อยละ 100.00 มีระยะเวลาเฉลี่ยในการแจ้งเตือน 2.49 วินาที และผู้ใช้งานมีความพึงพอใจอยู่ในระดับมากที่สุด ($\bar{x}$ = 4.71, S.D. = 0.38) ระบบสามารถบูรณาการการคำนวณดัชนีความร้อนแบบเรียลไทม์ การจำแนกระดับความเสี่ยงตามเกณฑ์ Heat Flag การเชื่อมโยงข้อมูลผ่านคลาวด์ และการแจ้งเตือนผ่าน LINE ภายในแพลตฟอร์มเดียว จึงช่วยสนับสนุนการบริหารจัดการความเสี่ยงจากความร้อนและการตัดสินใจด้านความปลอดภัยในการฝึกทหารได้อย่างมีประสิทธิภาพ นอกจากนี้ ผลการวิจัยยังแสดงให้เห็นถึงศักยภาพของการประยุกต์ใช้เทคโนโลยี IoT เพื่อพัฒนาระบบเฝ้าระวังและแจ้งเตือนแบบเรียลไทม์สำหรับงานภาคสนามและการปฏิบัติงานกลางแจ้ง รวมทั้งเป็นแนวทางเชิงวิชาการสำหรับพัฒนาระบบด้านความปลอดภัยในบริบทที่มีความเสี่ยงจากสภาพแวดล้อมในอนาคต

คำสำคัญ: อินเทอร์เน็ตของสรรพสิ่ง, ดัชนีความร้อน, การเฝ้าระวังแบบเรียลไทม์, การฝึกทหาร, การจัดการความเสี่ยงจากความร้อน

Abstract

Heat-related illness poses a significant risk to personnel safety and training effectiveness in military environments, while existing monitoring practices often lack real-time heat-risk assessment and alert capabilities. This study aimed to 1) develop an Internet of Things (IoT)-based real-time heat index monitoring and alert system for military training, 2) evaluate the technical performance of the developed system in terms of sensor validation, heat-risk rule-based classification verification, data transmission reliability, and alert latency, and 3) assess user satisfaction. This study employed a research and development (R&D) approach based on the System Development Life Cycle (SDLC). The developed system integrated an SHT31 temperature and humidity sensor, an ESP32 microcontroller, Firebase Realtime Database, a web-based dashboard, and a LINE Official Account. The study included all 40 personnel participating in the 2026 military discipline training program at the Directorate of Communications and Information Technology, Royal Thai Armed Forces Headquarters, using a census approach. Technical performance was evaluated through 50 predefined heat-risk classification test cases, 100 data transmission trials, and 10 alert latency measurements. The results demonstrated that the developed system achieved 100.00% correctness in heat-risk rule-based classification verification under controlled testing conditions and a 100.00% data transmission success rate, with an average alert latency of 2.49 seconds. Overall user satisfaction was rated at the highest level ($\bar{x}$ = 4.71, S.D. = 0.38). The system effectively integrates real-time heat index computation, military Heat Flag classification, cloud-based data synchronization, and instant LINE notifications within a single platform, thereby enhancing heat-risk monitoring and supporting timely safety decision-making during military training. These findings demonstrate the practical applicability of IoT-based real-time monitoring technologies for improving occupational safety in military training and other outdoor operational environments and provide a valuable framework for the future research and development of intelligent safety monitoring systems in high-risk settings.

Keywords: Internet of things, Heat index, Real-time monitoring, Military training, Heat-risk management

1. Introduction

Climate change and rising global temperatures have become major challenges affecting public health, occupational safety, and military readiness worldwide. The increasing frequency and intensity of extreme heat events have significantly elevated the risk of heat-related illnesses among individuals performing strenuous outdoor activities, particularly military personnel, emergency responders, and outdoor workers (Patton & Hoyt, 2023; Gibb et al., 2024). Heat-related illnesses range from mild conditions, such as heat cramps and heat exhaustion, to life-threatening heat stroke, which may result in multiple organ failure or death if not recognized and treated promptly (Epstein et al., 2025). Consequently, environmental heat has become an important non-combat hazard that directly affects personnel safety, operational performance, and training effectiveness in military organizations (Patton & Hoyt, 2023).

Thailand is located in a tropical region characterized by high temperatures and humidity throughout most of the year. Such environmental conditions substantially increase the risk of heat-related illnesses during outdoor military training. According to the Royal Thai Army Medical Department (2023), heat index values should be continuously monitored and classified according to the Heat Flag criteria to support decisions regarding hydration, work-rest cycles, and training intensity. However, many military units continue to rely on manual measurements or weather information obtained from centralized meteorological stations. These approaches may not accurately represent local microclimate conditions at the actual training site

and often delay risk assessment and operational decision-making, thereby increasing the likelihood of heat-related injuries.

Previous epidemiological research conducted among Royal Thai Army conscripts reported that 53 of 809 newly inducted conscripts (6.6%) developed heat-related illnesses during basic military training, highlighting that heat-related illness remains an important occupational health concern in military settings (Nutong et al., 2018). These findings underscore the need for effective real-time environmental monitoring and early warning systems capable of supporting timely operational decision-making and reducing heat-related risks during military training.

Recent studies have highlighted the growing importance of heat-risk surveillance and environmental monitoring in military and occupational settings. Narindrarangkura et al. (2024) demonstrated that predictive analytics could improve the surveillance of heat-related illnesses among Thai military recruits by enabling early identification of heat-risk factors. Similarly, Patton and Doyle (2024) reported increasing environmental heat exposure at U.S. Army basic combat training installations, emphasizing the need for more effective environmental monitoring to protect military personnel. Furthermore, the Defense Health Agency (2023) reported that continuous environmental surveillance and proactive heat-risk management are essential strategies for reducing severe heat-related illnesses during military operations and training. Although these studies provide valuable evidence for heat-risk prevention, they primarily focus on surveillance, prediction, or epidemiological analysis rather than the development of an integrated real-time monitoring and alert system for operational use.

Advances in the Internet of Things (IoT) have enabled intelligent environmental monitoring systems capable of collecting, processing, and transmitting environmental data in real time. IoT-based systems integrate sensing devices, wireless communication, cloud computing, and mobile applications to improve situational awareness and support rapid decision-making in safety-critical environments. Recent studies have demonstrated the effectiveness of IoT technologies for environmental monitoring and heat-alert prediction (Considine et al., 2023; Popescu et al., 2024). Nevertheless, most existing systems emphasize environmental data acquisition, visualization, or predictive analytics, while providing limited support for operational decision-making in military environments. To provide a clearer overview of existing studies, Table 1 compares representative heat monitoring and alert systems with respect to sensing technology, cloud integration, notification mechanisms, military-specific heat-risk classification, application domains, and existing limitations.

As shown in Table 1, previous studies have primarily focused on environmental monitoring, predictive analytics, or general heat-alert systems. However, none of these systems integrates real-time heat index computation, military Heat Flag classification, cloud-based synchronization, and instant LINE Official Account notification within a unified platform specifically designed for military training. Moreover, empirical validation of such systems under actual military training conditions remains limited.

Table 1 presents a comparative synthesis of the distinctive features and limitations of representative IoT-based heat-monitoring studies, including their sensing technologies, cloud platforms, notification mechanisms, military Heat Flag support, and application domains.

Table 1. Comparison of related IoT-based heat monitoring studies

Study	Sensor	Cloud Platform	Real-time Notification	Military Heat Flag	Application Domain	Limitation
Buller et al. (2021)	Wearable physiological sensors	Mobile cloud platform	✓ (Mobile application)	✗	Military heat injury prevention	No heat index or military heat-flag support
Narindrarangkura et al. (2024)	SHT31	Cloud Database	✓	✗	Occupational Health	No military application
Considine et al. (2023)	Meteorological Data	Cloud Analytics	✗	✗	Heat Alert Prediction	No IoT sensing platform
This Study	SHT31	Firebase Realtime Database	✓ (LINE OA)	✓	Military training	Integrated platform

Despite recent advances in IoT-based heat monitoring technologies, several research gaps remain: (1) existing studies have primarily focused on environmental monitoring or predictive analytics; (2) few studies have integrated real-time heat index computation, military Heat Flag classification, cloud synchronization, and instant LINE Official Account notifications within a single platform; and (3) empirical validation of integrated systems under actual military training conditions remains limited. Consequently, an integrated IoT-based solution is needed to provide real-time heat-risk assessment and decision support specifically for military training environments.

To address these research gaps, this study develops and evaluates an IoT-based real-time heat index monitoring and alert system specifically designed for military training. Unlike previous IoT-based environmental monitoring systems, the proposed platform integrates four key components within a single operational framework: (1) real-time heat index computation, (2) military Heat Flag classification based on Royal Thai Army guidelines, (3) cloud-based synchronization using Firebase Realtime Database, and (4) instant notification through the LINE Official Account. This integrated architecture supports real-time environmental monitoring and rapid operational decision-making during military training.

The main contributions of this study are fourfold. First, it develops an integrated IoT-based heat-risk monitoring platform tailored for military training environments. Second, it incorporates the Royal Thai Army Heat Flag criteria to automate heat-risk classification and support operational decision-making. Third, it combines cloud-based synchronization with instant LINE Official Account notifications to improve the timeliness of heat-risk communication. Finally, it evaluates the developed system through technical performance assessment, including heat-risk rule-based classification verification, data transmission success rate, and alert latency, together with user satisfaction under actual military training conditions.

Therefore, the objectives of this study were (1) to develop an IoT-based real-time heat index monitoring and alert system for military training; (2) to evaluate the technical performance of the developed system in terms of sensor validation, heat-risk rule-based classification verification, data transmission reliability, and alert latency; and (3) to assess user satisfaction regarding the effectiveness and usability of the system for supporting heat-risk management and safety decision-making during military training.

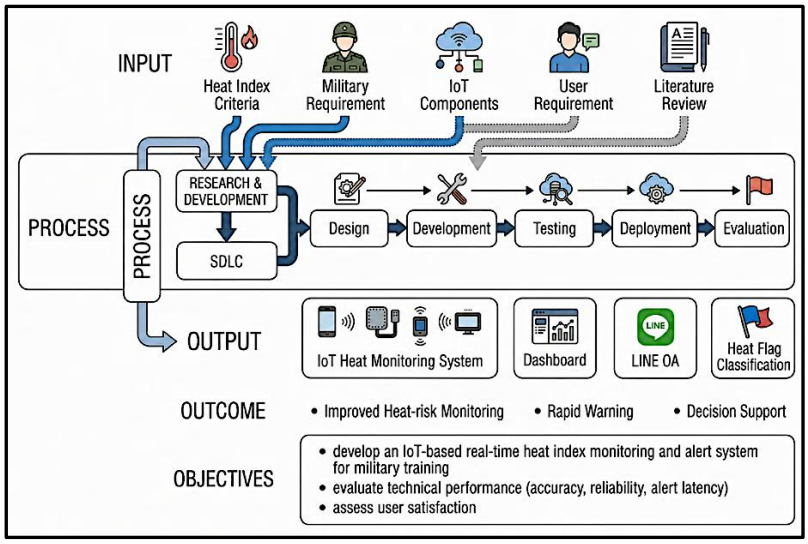


Figure 1. Conceptual framework for the proposed IoT-based real-time heat index monitoring and alert system

The conceptual framework illustrates the overall research process based on the Input–Process–Output (IPO) model. The framework begins with problem identification, military heat-risk criteria, IoT technologies, user requirements, and a literature review as research inputs. These inputs are integrated through a research and development (R&D) methodology using the System Development Life Cycle (SDLC), resulting in the development of the proposed IoT-based monitoring system. The developed system is subsequently evaluated through technical performance assessment and user satisfaction evaluation to achieve the three research objectives.

2. Materials and methods

2.1 Research Design

This study employed a research and development (R&D) methodology to design, implement, and evaluate an Internet of Things (IoT)-based real-time heat index monitoring and alert system for military training. The development process followed the System Development Life Cycle (SDLC), consisting of five phases: requirements analysis, system design, implementation, testing, and evaluation. The SDLC provides a systematic framework for developing reliable software systems and has been widely adopted for IoT applications because it facilitates the integration of sensing devices, cloud services, and user applications while improving system quality and maintainability (Pressman & Maxim, 2020; Fahmideh et al., 2022).

2.2 System Development

The overall architecture of the developed system is illustrated in Figure 2. The proposed platform consists of three functional layers: (1) an environmental sensing layer, (2) a cloud communication layer, and (3) an application layer. The sensing layer employed an SHT31 temperature and relative humidity sensor connected to an ESP32 microcontroller to continuously acquire environmental data. The measured data were transmitted through a wireless network to Firebase Realtime Database, which served as the cloud platform for real-time data synchronization and storage. Heat index values were automatically calculated using the National Weather Service heat index equation. The calculated values were subsequently classified according to the Royal Thai Army Heat Flag criteria to determine the corresponding heat-risk level.

The processed information was presented through a web-based dashboard, while heat-risk alerts were automatically delivered to users through the LINE Official Account using Flex Message.

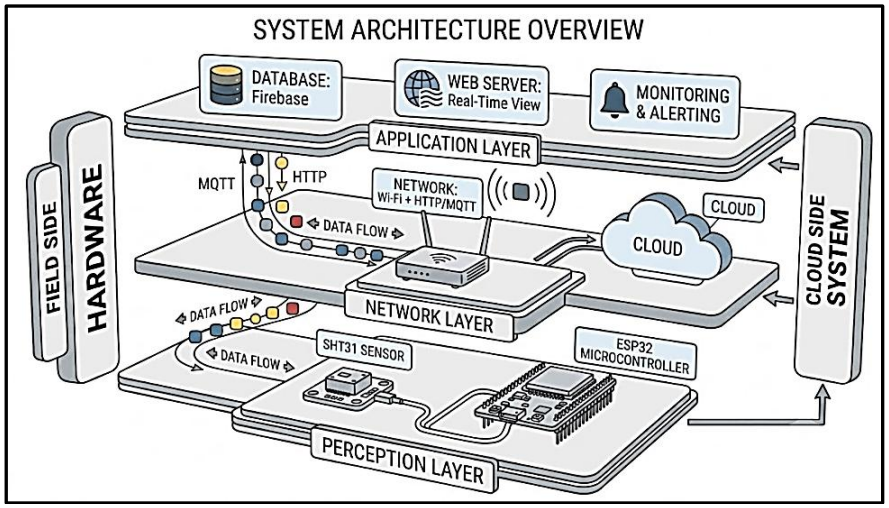


Figure 2. Architecture of the proposed IoT-based heat index monitoring and alert system

The developed system integrates hardware for environmental data acquisition with software services for data storage, visualization, and real-time notification. The specifications and functions of the principal components are summarized in Table 2.

To support automated operational decision-making, the calculated heat index was mapped to five Heat Flag levels and corresponding recommendations for military training activities, as shown in Table 3.

Table 2. Hardware and software components used in the developed system

Component	Specification	Function
ESP32	Wi-Fi-enabled microcontroller	Data processing and communication
SHT31	Temperature and humidity sensor	Environmental monitoring
OLED Display	0.96-inch I2C display	On-site data visualization
Firebase Real-time Database	Cloud database platform	Data storage and synchronization
LINE Messaging API	Messaging platform	Real-time notification delivery
Web Dashboard	HTML/CSS/JavaScript	Monitoring and data visualization

Table 3. Heat-risk classification based on heat index criteria

Heat flag	Heat index (°C)	Recommended training activity
White	< 27	Normal training
Green	27–32	Increased hydration monitoring
Yellow	33–39	Reduced training intensity
Red	40–51	Increased rest periods
Black	> 51	Training suspension recommended

2.3 Study Site and Participants

The study population consisted of military personnel who participated in the 2026 personnel discipline training program at the Directorate of Communications and Information Technology, Royal Thai Armed Forces Headquarters. These personnel were directly involved in outdoor military training and heat-risk management, including training supervisors, drill instructors, assistant instructors, medical officers, and military personnel representatives.

A census approach was employed, whereby all 40 eligible personnel were included in the study. The participants comprised five training supervisors, five medical officers, fifteen drill instructors, ten assistant instructors, and five military personnel representatives. Since the entire target population participated in the evaluation, no sampling procedure was required. The participants were responsible for training management, operational supervision, or medical support during field exercises, enabling them to evaluate both the technical performance and practical usability of the developed system under actual operational conditions (Creswell & Creswell, 2023).

This study involved the evaluation of a prototype IoT-based monitoring system and an anonymous user satisfaction survey. Participation was voluntary, and participants were informed of the study objectives prior to participation. No personally identifiable information was collected, and all responses were anonymized and kept confidential. Participants were free to decline or withdraw from the study without any consequences. Formal ethical approval was not obtained prior to data collection. This information has been transparently disclosed to the Editorial Board for consideration in accordance with the journal's ethical requirements.

Technical performance evaluation was conducted independently of participant assessment. The evaluation design was based on system and software quality measurement principles, particularly functional correctness, reliability, and time behavior. The heat-risk rule-based classification verification was evaluated using 50 predefined test cases, consisting of 10 cases for each Heat Flag level: WHITE, GREEN, YELLOW, RED, and BLACK. This design ensured balanced coverage of all predefined risk categories and allowed verification of the system's classification correctness under different environmental conditions. Data transmission reliability was assessed through 100 consecutive communication trials to verify the stability of data transfer from the ESP32 microcontroller to Firebase Realtime Database. Alert latency was measured across 10 repeated notification trials to evaluate the consistency of real-time notification delivery through the LINE application. These testing procedures were designed according to the quality measurement concepts of ISO/IEC 25023 and software testing principles recommended for validating functional correctness and system reliability (ISO/IEC 25023, 2016; Pressman & Maxim, 2020).

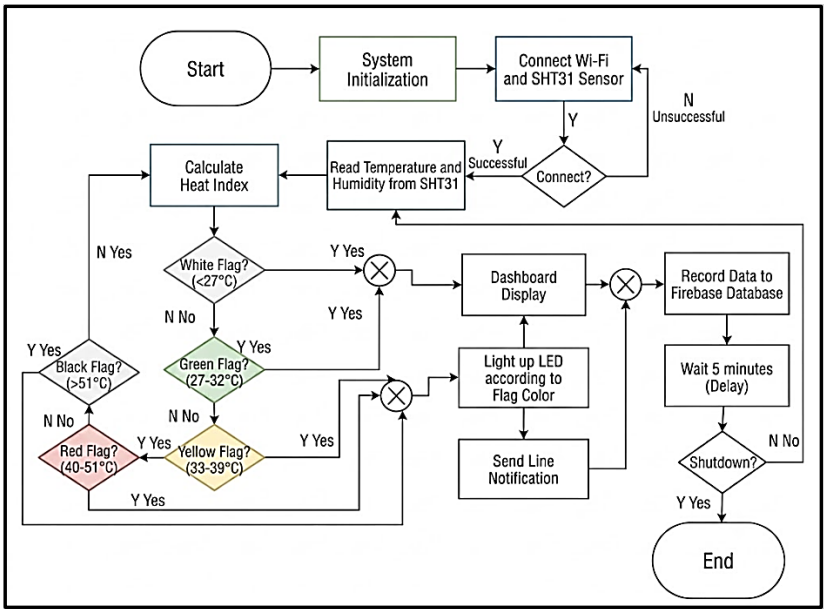


Figure 3. Workflow of data acquisition, heat index calculation, and real-time alert generation

2.4 Field Deployment and Data Collection

The developed system was deployed under actual military training conditions over a 10-day field deployment conducted from 3 to 12 May 2026. Environmental monitoring was performed daily from 08:00 to 16:00, corresponding to the period of highest heat exposure during routine military training. Ambient temperature (°C) and relative humidity (%RH) were automatically recorded at 1-minute intervals, resulting in approximately 4,800 environmental observations. Heat index values were computed in real time and synchronized with Firebase Realtime Database for continuous visualization through the web dashboard. Whenever the calculated heat index exceeded the predefined Heat Flag thresholds, the system automatically issued heat-risk notifications via the LINE Official Account. Participants were able to monitor real-time environmental conditions, Heat Flag statuses, and alert notifications through both the web dashboard and mobile devices.

2.5 Performance Evaluation

The developed system was evaluated using both technical performance assessment and user satisfaction assessment. Technical performance was assessed using four evaluation criteria: (1) sensor validation, performed by comparing SHT31 measurements with those of a calibrated digital thermo-hygrometer before field deployment; (2) heat-risk rule-based classification verification, evaluated using 50 predefined heat index test cases covering all Heat Flag categories defined by the Royal Thai Army Medical Department. To further verify the correctness of the classification algorithm around decision thresholds, boundary-value test cases were additionally included. The test cases were selected at values immediately below, equal to, and immediately above each Heat Flag threshold (e.g., 27°C, 33°C, 40°C, and 51°C) to ensure that the developed system correctly classified heat-risk levels at boundary conditions; (3) data transmission success rate, evaluated through 100 consecutive transmission trials between the ESP32 microcontroller and Firebase Realtime Database; and (4) alert latency, evaluated using 10 repeated notification tests, for which latency was defined as the elapsed time between environmental data acquisition and successful delivery of the notification through the LINE Official Account.

The field deployment was designed to evaluate the system under actual military training conditions. The study period, operating hours, sampling interval, number of records, observed environmental ranges, and deployment site are summarized in Table 4.

Table 4. Field deployment conditions

Parameter	Value
Study period	3–12 May 2026
Experimental duration	10 consecutive days
Operating hours	08:00–16:00
Sampling interval	Every 1 minute
Records collected per day	Approximately 480
Total environmental records	Approximately 4,800
Temperature range	30.8–37.4°C
Relative humidity range	58–86%RH
Study site	Signal Battalion, Directorate of Communications and Information Technology, Royal Thai Armed Forces Headquarters

The number of test cases and repeated trials was selected based on recommendations for software functional testing and IoT system performance evaluation, ensuring adequate repeatability and reliability of the experimental results (ISO/IEC 25023, 2016; Pressman & Maxim, 2020).

Following the field deployment, participants evaluated the developed system using a structured questionnaire covering four dimensions: (1) technical performance and hardware, (2) user interface and notification, (3) usefulness and practical applicability, and (4) system reliability and acceptance. Responses were recorded using a five-point Likert scale.

Questionnaire Validation and Reliability. The user satisfaction questionnaire was evaluated for content validity by three experts in information systems and software development. The Item–Objective Congruence (IOC) values ranged from 0.67 to 1.00, with an average IOC of 0.83, indicating acceptable content validity. A pilot study was subsequently conducted to assess the reliability of the questionnaire. The instrument demonstrated good internal consistency, with a Cronbach's alpha coefficient of 0.89.

System Quality Evaluation. Prior to user evaluation, the developed system was assessed by three experts. The overall system quality was rated at a high level ($\bar{x}$ = 4.18, S.D. = 0.55), confirming that the system was appropriate for field deployment and subsequent user satisfaction evaluation.

2.6 Performance Metrics

The performance of the developed IoT-based real-time heat index monitoring and alert system was evaluated in four areas: sensor validation, heat-risk rule-based classification verification, data transmission reliability, and alert latency. The evaluation was conducted to verify whether the system could reliably acquire environmental data, correctly implement the predefined Heat Flag classification rules, successfully transmit data to the cloud database, and deliver alert messages within an appropriate response time for real-time military training safety management.

For heat-risk rule-based classification verification, 50 predefined test cases were used, with 10 cases assigned to each of the five Heat Flag categories to ensure balanced verification across all predefined risk levels. For data transmission reliability, 100 consecutive transmission attempts were conducted to provide sufficient repeated observations for identifying possible communication failures or data loss during cloud synchronization. For alert latency, 10 repeated notification trials were considered appropriate because latency measurement focused on short response-time behavior under the same operational workflow. Repeated measurements helped verify whether the notification delay remained stable during real-time operation. This evaluation design aligns with ISO/IEC 25023, which emphasizes measurable indicators for software product quality, including functional correctness, reliability, and time behavior.

2.6.1 Sensor Validation

Before performance testing, the SHT31 sensor was validated against a standard digital thermo-hygrometer placed at the same location. Temperature and relative humidity were recorded simultaneously from both devices to examine measurement differences, consistency, and output stability before using the data for heat index calculation. The results showed that the SHT31 readings remained within an acceptable range, indicating that the sensor was suitable for environmental monitoring in the developed system.

2.6.2 Heat Index Calculation

Heat index values were calculated from the air temperature and relative humidity measured by the SHT31 sensor using the Rothfusz regression adopted by the U.S. National Weather Service (Rothfusz, 1990), as shown in Equation (1). The calculated values were subsequently used to classify heat-risk levels according to the predefined Heat Flag criteria.

$$HI = c_1 + c_2T + c_3RH + c_4TRH + c_5TT^2 + c_6RH^2 + c_7T^2RH + c_8TRH^2 + c_9T^2RH^2 \quad (1)$$

where HI = heat index (°F)

T = air temperature (°F)

RH = relative humidity (%)

$c_1, c_{2,\ldots}, c_9$ = The empirical constants in the NOAA Rothfusz regression are $c_1 = -42.379$, $c_2 = 2.04901523$, $c_3 = 10.14333127$, $c_4 = -0.22475541$, $c_5 = -0.00683783$, $c_6 = -0.05481717$, $c_7 = 0.00122874$, $c_8 = 0.00085282$, and $c_9 = -0.00000199$.

The temperature measured by the SHT31 sensor was initially obtained in degrees Celsius and converted to degrees Fahrenheit before being entered into the NOAA Rothfusz regression. The calculated heat index was subsequently converted from degrees Fahrenheit back to degrees Celsius for classification according to the Royal Thai Army Heat Flag criteria.

$$T_F = (T_C \, x \, \frac{9}{5}) + 32 \quad (2)$$

$$HI_C = (HI_F - 32) \times \frac{5}{9} \quad (3)$$

2.6.3 Heat-risk rule-based classification verification

Heat-risk rule-based classification verification was performed by comparing the Heat Flag level generated by the system with the expected Heat Flag level determined from the predefined criteria. The percentage of correctly classified test cases was calculated using Equation (4).

$$RCV\ (\%) = \frac{N_c}{N_t} \tag{4}$$

where $RCV(\%)$ = rule-based classification verification result of the developed system expressed as a percentage (%)

N_c = number of correctly classified test cases

N_t = total number of test cases evaluated

The heat-risk rule-based classification verification was evaluated using 50 test cases covering all predefined heat-risk categories, including WHITE, GREEN, YELLOW, RED, and BLACK levels. The test cases were generated from different combinations of temperature and relative humidity values representing a wide range of environmental conditions that may occur during military training activities. Using multiple test cases across all classification levels helps ensure that the developed system can consistently classify heat-risk conditions under various environmental scenarios and improves the reliability of the performance evaluation (ISO/IEC 25023, 2016; Pressman & Maxim, 2020).

2.6.4 Alert latency

Alert latency was defined as the time interval between data acquisition by the sensor and successful delivery of the alert message to the user through the LINE application. Alert latency was calculated using Equation (5).

$$Latency = T_a - T_s \tag{5}$$

where $Latency$ = alert latency (s)

T_a = alert reception timestamp

T_s = sensor acquisition timestamp

The average alert latency was calculated using Equation (6).

$$\bar{L} = \frac{1}{n}\sum_{i=1}^{n} L_i \tag{6}$$

where $\bar{L}$ = average alert latency (s)

L_i = latency measured in the i^{th} test trial (s)

n = total number of test trials

2.6.5 User Satisfaction Evaluation

User satisfaction was evaluated using a five-point Likert scale questionnaire. The questionnaire covered four evaluation dimensions: (1) technical performance and hardware, (2) user interface and notification, (3) usefulness and practical applicability, and (4) system reliability and acceptance. The mean and standard deviation were used to summarize user satisfaction scores.

The mean score was calculated using Equation (7).

$$\bar{x} = \frac{\sum_{i=1}^{n} x_i}{n} \quad (7)$$

where $\bar{x}$ = mean score
x_i = score obtained by each participant
n = total number of participants

The standard deviation was calculated using Equation (8).

$$S.D. = \sqrt{\frac{\sum_{i=1}^{n}(x_i - \bar{x})^2}{N-1}} \quad (8)$$

where $S.D.$ = standard deviation
x_i = score obtained by each participant
$\bar{x}$ = mean score
N = total number of participants

To evaluate the reliability of data transmission, the success rate was calculated using Equation (9):

$$\textbf{Success Rate (\%)} = \frac{N_s}{N_t} \, x \, 100 \quad (9)$$

where **Success Rate** (%) = percentage of successful data transmissions
N_s = number of successful data transmissions
N_t = total number of data transmission attempts

2.6.6 System Operation for Performance Evaluation

The system operation began when the ESP32 microcontroller initialized the hardware and established a connection with the Wi-Fi network and SHT31 sensor. After a successful connection, the sensor measured air temperature and relative humidity. The measured values were then transmitted to the ESP32 for heat index calculation. The calculated heat index was classified into heat-risk levels according to the Heat Flag criteria, including white, green, yellow, red, and black levels.

After classification, the system displayed the results on the web dashboard and activated the LED indicator according to the detected risk level. If the heat-risk level reached a warning condition, the system automatically sent an alert message through the LINE Official Account. All environmental data and heat-risk results were stored in Firebase Realtime Database for real-time monitoring and historical data review. The system repeated the monitoring cycle every minute unless the device was turned off.

2.7 Statistical Analysis

Descriptive statistics were employed to analyze the collected data. The mean ($\bar{x}$) and standard deviation (S.D.) were used to summarize user satisfaction scores, while appropriate descriptive measures were used for the technical performance metrics. The results were interpreted according to commonly accepted criteria for Likert-scale evaluation in information systems research (Creswell & Creswell, 2023).

3. Results

During the field deployment, the proposed system continuously monitored environmental conditions over a 10-day evaluation period. A total of approximately 4,800 environmental records were successfully collected and synchronized with Firebase Realtime Database without data loss. The recorded temperature ranged from 30.8°C to 37.4°C, while the relative humidity varied between 58% and 86%. These environmental conditions covered multiple heat-risk levels, enabling comprehensive evaluation of the developed monitoring and alert system.

3.1 Development of the IoT-Based Real-Time Heat Index Monitoring and Alert System

The first objective of this study was to develop an IoT-based real-time heat index monitoring and alert system for military training. The developed system integrated an SHT31 temperature and humidity sensor, an ESP32 microcontroller, Firebase Realtime Database, a web-based dashboard, and a LINE Official Account notification service.

Environmental data were continuously collected and transmitted to the cloud for real-time processing. The system calculated the heat index (HI) using the National Weather Service (NWS) algorithm based on the Rothfusz regression (Rothfusz, 1990) and classified heat-risk levels according to the Royal Thai Army Heat Flag criteria. The calculated results were displayed on both the OLED display and the web dashboard, while hazardous conditions automatically triggered warning notifications via the LINE Messaging API.

The developed prototype and its operational interfaces are shown in Figures 4 and 5.



Figure 4. Photograph of the developed IoT-based real-time heat index monitoring and alert system prototype for military training environments

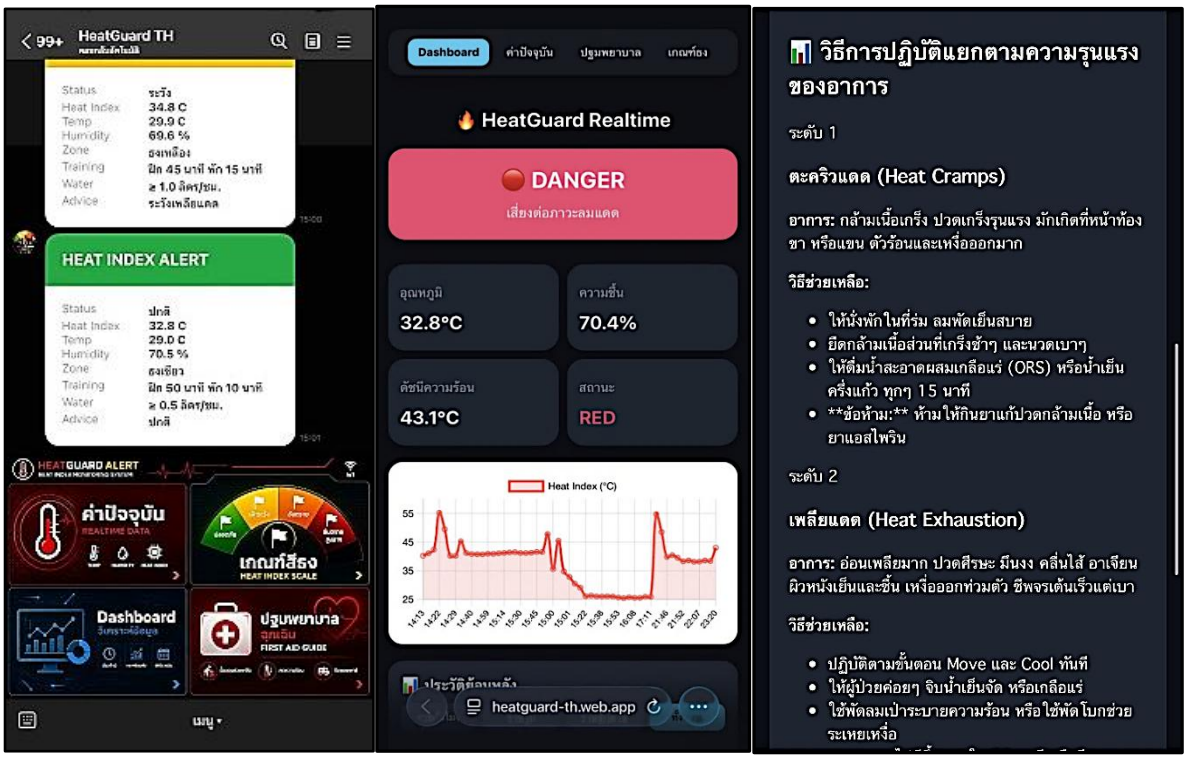


Figure 5. Screenshot of the developed real-time monitoring dashboard displaying environmental conditions and heat-risk levels

During field deployment, the platform operated continuously under actual military training conditions at the Signal Battalion, Directorate of Communications and Information Technology, Royal Thai Armed Forces Headquarters. The system demonstrated stable operation throughout the testing period and supported real-time heat-risk monitoring during military training activities.

3.2 Field Deployment and Real-Time System Operation

The developed IoT-based heat index monitoring system was deployed and evaluated under actual military training conditions over a 10-day field deployment conducted from 3 to 12 May 2026. Environmental monitoring was performed daily from 08:00 to 16:00, corresponding to the period of highest heat exposure during routine military training. Ambient temperature (°C) and relative humidity (%RH) were automatically recorded at 1-minute intervals, resulting in approximately 4,800 environmental observations. The collected data were processed in real time to calculate the heat index and synchronized with Firebase Realtime Database for continuous visualization through the web dashboard.

Whenever the calculated heat index reached or exceeded the predefined Heat Flag thresholds, the system automatically generated heat-risk notifications through the LINE Official Account. These notifications enabled instructors, medical personnel, and commanders to receive timely alerts and monitor current environmental conditions, Heat Flag statuses, and associated risk levels using both the web dashboard and mobile devices. The automated notification mechanism supported prompt decision-making for implementing appropriate heat-risk mitigation measures during military training. Overall, the field deployment results demonstrated that the proposed system operated continuously and reliably under real-world conditions. The integration of real-time environmental monitoring, automated heat index computation, cloud-based data synchronization, and instant LINE notifications provided effective operational support for heat-risk surveillance and safety management throughout the training period.

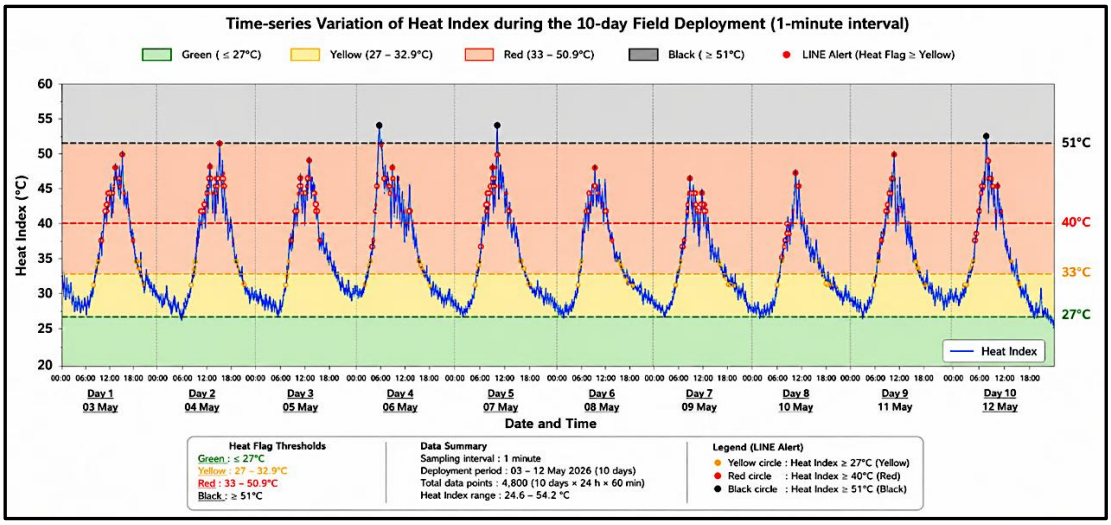


Figure 6. Time-series variation in the heat index during the 10-day field deployment. The system continuously monitored environmental conditions and synchronized data in real time, demonstrating stable operation under actual military training conditions

3.3 Technical Performance Evaluation of the Developed System

The second objective of this study was to evaluate the technical performance of the developed IoT-based heat index monitoring system in terms of sensor measurement agreement, heat-risk rule-based classification verification, alert latency, and data transmission reliability. The accuracy of the environmental sensing module was first evaluated by comparing measurements obtained from the SHT31 sensor with those from a calibrated digital thermo-hygrometer.

Sensor validation was performed by comparing simultaneous temperature and relative humidity readings from the SHT31 sensor with those from a calibrated digital thermo-hygrometer. The comparison results and measurement differences are presented in Table 5.

Table 5. Sensor validation results

Parameter	Reference Device	SHT31 Sensor	Difference	Interpretation
Temperature (°C)	32.7	32.8	0.1	Acceptable
Relative Humidity (%)	70.2	70.4	0.2	Acceptable

The SHT31 sensor produced measurements that closely matched those of the reference instrument, with differences of 0.1°C for temperature and 0.2% for relative humidity. These deviations were within acceptable limits for heat index computation and environmental monitoring.

Following sensor validation, representative temperature and relative-humidity values were used to demonstrate the heat index calculation and the resulting Heat Flag classification across the five risk levels, as shown in Table 6.

Table 6. Examples of heat index calculations and heat-risk classification results

Log ID	Temperature (°C)	Relative Humidity (%)	Heat Index (°C)	Heat Flag Level
L001	19.8	45.00	25.3	WHITE
L002	26.5	54.70	27.2	GREEN
L003	31.0	72.40	38.5	YELLOW
L004	32.8	70.40	43.1	RED
L005	34.9	78.30	54.8	BLACK

The calculated heat index increased as temperature and relative humidity rose, resulting in corresponding heat-risk classifications ranging from WHITE (safe conditions) to BLACK (extreme heat-risk conditions). These examples demonstrate the capability of the developed system to automatically compute the heat index and classify heat-risk levels according to the Royal Thai Army Heat Flag criteria. To evaluate the rule-based classification performance, 50 predefined test cases representing all Heat Flag categories were examined. In addition, boundary-value test cases were conducted to verify the correctness of the classification algorithm at decision thresholds.

To verify classification performance at critical decision points, boundary-value tests were conducted using heat index values immediately below, equal to, and immediately above the predefined thresholds. The expected classifications, system outputs, and verification results are presented in Table 7.

The boundary-value verification demonstrated that the developed system correctly classified all heat-risk levels at values immediately below, equal to, and immediately above each predefined Heat Flag threshold. These results indicate that the classification algorithm consistently handled decision boundaries without misclassification.

After boundary-value verification, the rule-based classification algorithm was evaluated using 50 predefined test cases distributed equally across the five Heat Flag levels. The number of correct classifications and the verification percentage for each level are summarized in Table 8.

Table 7. Boundary-value verification results for Heat Flag classification

Case	Heat Index (°C)	Expected Heat Flag	System Output	Result
B01	26.9	White	White	√
B02	27.0	Green	Green	√
B03	27.1	Green	Green	√
B04	32.9	Green	Green	√
B05	33.0	Yellow	Yellow	√
B06	33.1	Yellow	Yellow	√
B07	39.9	Yellow	Yellow	√
B08	40.0	Red	Red	√
B09	40.1	Red	Red	√
B10	51.0	Red	Red	√
B11	51.1	Black	Black	√

Table 8. Heat-risk rule-based classification verification results

Heat flag level	Number of test cases	Correctly classified test cases	Verification result (%)
WHITE	10	10	100
GREEN	10	10	100
YELLOW	10	10	100
RED	10	10	100
BLACK	10	10	100
Total	50	50	100

All 50 predefined test cases under controlled testing conditions were classified correctly, resulting in a rule-based classification correctness rate of 100.00%. This result verifies that the developed system correctly implemented the predefined Heat Flag classification rules for the tested cases.

The responsiveness of the notification module was assessed by measuring the elapsed time between environmental data acquisition and successful notification delivery through the LINE Official Account. The latency results are presented in Table 9. The measured alert latency ranged from 2.41 to 2.58 s, with an average response time of 2.49 s.

The reliability of wireless data transmission was assessed using 100 consecutive communication trials. The results are presented in Table 10.

All transmitted data were successfully synchronized with Firebase Realtime Database during the evaluation period, resulting in a data transmission success rate of 100.00%.

The responsiveness of the notification module was assessed across 10 repeated trials by measuring the elapsed time from environmental data acquisition to successful delivery through the LINE Official Account. The latency recorded in each trial and the average latency are presented in Table 9.

Data transmission reliability was evaluated through 100 consecutive attempts from the ESP32 microcontroller to Firebase Realtime Database. The numbers of successful and failed transmissions, along with the resulting success rate, are summarized in Table 10.

Table 9. Alert latency measurements.

Test trial	Alert latency (s)
1	2.41
2	2.53
3	2.46
4	2.58
5	2.47
6	2.50
7	2.51
8	2.48
9	2.52
10	2.44
Average Latency	**2.49**

Table 10. Data transmission success rate

Performance indicator	Value
Total transmission attempts (N_t)	100
Successful transmissions (N_s)	100
Failed transmissions	0
Success Rate (%)	100.00

3.4 User Satisfaction Evaluation

The third objective of this study was to evaluate user satisfaction with the developed IoT-based real-time heat index monitoring and alert system for supporting heat-risk management during military training.

A total of 40 participants, including training supervisors, drill instructors, assistant instructors, medical personnel, and military personnel representatives, participated in the user satisfaction evaluation. The assessment was conducted using a five-point Likert scale questionnaire covering four evaluation dimensions: (1) technical performance and hardware, (2) user interface and notification, (3) usefulness and practical applicability, and (4) system reliability and acceptance.

Overall user satisfaction was rated at the highest level, with a mean score of 4.71 and a standard deviation of 0.38, indicating a high level of acceptance of the developed system. The detailed evaluation results are presented in Table 11.

Among the four evaluation dimensions, User Interface and Notification received the highest satisfaction score ($\bar{x}$ = 4.90, S.D. = 0.24). Participants expressed high satisfaction with the LINE Flex Message notifications, the accessibility provided by the LINE Rich Menu, and the dashboard interface, which enabled rapid access to real-time environmental information and heat-risk status.

The Usefulness and Practical Applicability dimension achieved the second-highest score ($\bar{x}$ = 4.69, S.D. = 0.42). Respondents indicated that the developed system effectively supported real-time monitoring of environmental conditions, facilitated adherence to the military Heat Flag criteria, and was suitable for practical deployment during military training activities.

The Technical Performance and Hardware dimension received a satisfaction score of $\bar{x}$ = 4.65 (S.D. = 0.39), demonstrating high user satisfaction with the performance of the SHT31 sensor, wireless data transmission, and the hardware components used in the system.

The System Reliability and Acceptance dimension received a satisfaction score of $\bar{x}$ = 4.61 (S.D. = 0.46). Participants reported confidence in the accuracy of the displayed information, trusted the system to support operational decision-making, and expressed willingness to continue using the system in future military training operations.

Participants reported high levels of satisfaction across all evaluation dimensions. The developed IoT-based heat index monitoring and alert system was well accepted by end users and demonstrated high usability, practical applicability, and reliability for supporting heat-risk management during military training.

User satisfaction was evaluated among 40 participants across four dimensions covering technical performance, interface and notification, practical usefulness, and system reliability and acceptance. The mean, standard deviation, and interpretation for each dimension are presented in Table 11.

Table 11. User satisfaction by evaluation dimension (n = 40)

Evaluation Dimension	Mean ($\bar{X}$)	S.D.	Interpretation
Technical Performance and Hardware	4.65	0.39	Highest
User Interface and Notification	4.90	0.24	Highest
Usefulness and Practical Applicability	4.69	0.42	Highest
System Reliability and Acceptance	4.61	0.46	Highest
Overall Satisfaction	4.71	0.38	Highest

3.5 Summary of System Performance Evaluation

To provide an overall view of the system evaluation, the key performance indicators obtained from the technical performance assessment and user satisfaction evaluation are summarized in Table 12. The table consolidates the principal findings reported in the preceding sections without further interpretation.

The principal technical and user-satisfaction indicators and their interpretations are summarized in Table 12.

Table 12. Summary of the overall system performance evaluation results

Performance Metric	Result	Interpretation
Heat-risk rule-based classification verification	100.00%	All test cases correctly classified
Data Transmission Success Rate	100.00%	No communication failure observed
Average Alert Latency	2.49 s	Average notification response time
User Satisfaction	$\bar{x}$ = 4.71, S.D. = 0.38	Highest satisfaction level

4. Discussion

The findings demonstrate that the proposed IoT-based real-time heat index monitoring and alert system successfully achieved the research objectives by correctly implementing the predefined Heat Flag classification rules, maintaining reliable cloud communication, providing rapid alert delivery, and achieving high user acceptance. Unlike previous IoT-based environmental monitoring systems, the proposed platform integrates real-time heat index computation, Royal Thai Army Heat Flag classification, cloud synchronization, dashboard visualization, and instant LINE Official Account notifications into a unified framework for military training. This integration extends earlier studies that primarily focused on environmental monitoring or heat prediction without directly supporting operational decision-making (Buller et al., 2021; Popescu et al., 2024).

Rule-based classification verification demonstrated 100.00% correctness across 50 predefined test cases under controlled conditions. This result confirms that the classification algorithm correctly implemented the standardized Royal Thai Army Heat Flag criteria for the tested cases. Because the classification mechanism applies explicit threshold-based decision rules, the result should be interpreted as verification of rule implementation rather than as predictive classification accuracy. This finding is consistent with previous studies showing that rule-based environmental monitoring systems based on standardized operational criteria provide reliable and reproducible decision support for safety-critical applications (Royal Thai Army Medical Department, 2023; Buller et al., 2021).

Although the proposed system achieved 100% correctness in the predefined rule-based classification tests, this result should be interpreted as verification of rule implementation rather than evidence of predictive accuracy or universal performance across all operational environments. The generalizability of the findings may be limited because the evaluation was conducted using predefined Heat Flag criteria and controlled testing conditions. Further validation under diverse environmental conditions and multiple deployment sites is recommended.

The average alert latency of 2.49 seconds indicates that the developed system provided near real-time heat-risk notifications under the conditions of this study. This performance can be attributed to the integration of the ESP32 microcontroller, Firebase Realtime Database, and the LINE Messaging API, which enabled rapid data transmission, cloud synchronization, and notification delivery. Furthermore, the 100.00% data transmission success rate demonstrates the reliability of the proposed communication architecture during the evaluation period. These findings are consistent with previous studies reporting the effectiveness of cloud-based IoT monitoring systems for real-time environmental monitoring (Fahmideh et al., 2022).

The high user-satisfaction rating ($\bar{x}$ = 4.71, S.D. = 0.38) indicates strong user acceptance of the developed system. This positive outcome can be attributed to the system's real-time monitoring capability, intuitive web-based dashboard, and instant heat-risk notifications delivered through the LINE Official Account, which enabled users to access timely environmental information and make rapid decisions during military training. In addition, the use of the LINE Official Account, a widely adopted communication platform in Thailand, reduced the learning curve and facilitated user adoption. These findings are consistent with Narindrarangkura et al. (2024), who reported that familiar communication platforms and user-centered interface design contribute significantly to technology acceptance and user satisfaction.

Compared with previous IoT-based heat monitoring systems, the proposed platform integrates environmental sensing, automated heat index computation, military-specific heat-risk classification, cloud synchronization, dashboard visualization, and instant notification within a single operational platform. This integrated architecture supports timely decision-making during military training and can also be adapted to other outdoor occupations, such as construction, agriculture, disaster response, and industrial maintenance, where localized heat-risk monitoring is essential (Defense Health Agency, 2023; Patton & Hoyt, 2023).

This study has several limitations. The evaluation was conducted at a single military training unit, limiting the generalizability of the findings. Although the SHT31 sensor was validated against a reference digital thermo-hygrometer, future studies should use certified calibration equipment. Further research should also validate the system across multiple sites, incorporate multisensor environmental mapping and artificial intelligence-based prediction, and evaluate its long-term effectiveness in reducing heat-related illness.

Overall, the findings indicate that combining standardized military heat-risk criteria with IoT sensing, cloud communication, and real-time notification provides an effective decision-support platform for heat-risk management in military training and other outdoor occupational environments.

To position the contribution of the proposed system in relation to prior work, representative heat-monitoring and alert systems were compared in terms of heat index calculation, cloud support, real-time notification, military Heat Flag integration, field validation, and application context, as shown in Table 13.

Table 13. Comparison of representative IoT-based heat monitoring and alert systems

Study	Heat Index Calculation	Cloud Platform	Real-time Notification	Military Heat Flag	Field Validation	Application
Buller et al. (2021)	✗	✓	✓ (Mobile App)	✗	✗	Military heat injury prevention
Narindrarangkura et al. (2024)	✓	✓	✗	✗	✓	Military Health Surveillance
Considine et al. (2023)	✗	✓	✗	✗	✗	Heat alert prediction
This study	✓	✓	LINE Official Account	✓	✓	Military training

5. Conclusions and Recommendations

5.1 Conclusions

This study presented an IoT-based platform for real-time heat index monitoring and automated heat-risk alerts to support military training. Field evaluation showed that the platform consistently classified heat-risk levels, maintained reliable communication with the cloud database, delivered notifications with minimal delay, and received positive evaluations from users.

The findings suggest that integrating environmental sensing, cloud-based data synchronization, and rule-based heat-risk classification provides practical support for heat-risk management during outdoor military activities. Continuous monitoring enables commanders and training personnel to respond more promptly to changing environmental conditions and implement preventive measures before heat-related illnesses occur.

The successful deployment under operational conditions further indicates that the proposed platform can be applied beyond controlled laboratory settings. Its modular architecture also provides a foundation for adapting the system to other outdoor occupations where heat exposure is a significant safety concern, including construction, agriculture, emergency response, and industrial field operations.

5.2 Limitations and Future Research

This study was conducted at a single military training unit, and system performance was evaluated under the environmental conditions encountered at that site. Consequently, the findings should be interpreted within the context of the study setting, and additional validation in different operational environments would strengthen their generalizability.

The reported 100.00% classification result represents rule-based classification correctness for predefined Heat Flag test cases under controlled conditions, rather than predictive accuracy across all operational environments. Further validation under diverse climatic conditions, multiple deployment sites, and long-term field use is therefore required to improve the generalizability of the findings.

Future studies should examine system performance across multiple military training locations, seasons, and climatic conditions. Incorporating wearable physiological sensors, such as heart rate and body temperature monitoring, together with artificial intelligence for personalized heat-risk prediction, may further enhance early warning capabilities and support more informed decision-making during outdoor training. Long-term deployment studies could also provide valuable evidence regarding system reliability, user adoption, and operational sustainability.

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