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Heat Stress Risk of Construction Workers in Semi-Arid Coastal Areas: Evidence from East Sumba, Indonesia

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ABSTRACT
Extreme heat poses a serious hazard for construction workers in tropical semi-arid regions, affecting safety, productivity, and health. This study investigated heat stress risk perception and contributing factors among 78 construction workers in East Sumba, Indonesia, comprising 40 non-local workers (51.3%) and 38 local workers (48.7%). Data were collected during 2023–2024 through on-site environmental measurements and structured interviews at eight active construction sites. Wet Bulb Globe Temperature (WBGT) measurements indicated consistently high-risk heat exposure conditions, particularly between 11:00 a.m. and 3:00 p.m. Independent-samples t-tests showed no significant differences between local and non-local workers in heat risk perception and preventive awareness (p-values > 0.05). However, local workers demonstrated higher acclimatization and thermal tolerance than non-local workers. Heat-related symptoms were reported by 15 workers (19.2%), including fever, dizziness, excessive thirst, and fainting. Smoking, insufficient sleep, and low body mass index were associated with increased vulnerability. These findings highlight the need for WBGT-based work–rest schedules, shaded rest areas, the provision of drinking water, and targeted heat-stress training, particularly for non-local workers.

Keywords: *Heat Stress; Construction Workers; Tropical semi-arid regions; Wet Bulb Globe Temperature (WBGT).*

1. Introduction

The construction sector is one of the most heat-exposed occupational domains globally, as workers frequently perform heavy physical tasks under direct solar radiation and with limited access to shade [1], [2], [3], [4], [5]. In tropical climates, this exposure is intensified by high ambient temperatures, high humidity, and low wind velocity, which collectively impair the body's thermoregulatory capacity [6], [7], [8]. Prolonged exposure to such environmental conditions can lead to heat-related illnesses (HRI), ranging from dehydration and heat exhaustion to heat stroke [9], [10], [11].

The Wet Bulb Globe Temperature (WBGT) index has been widely adopted as a practical indicator for assessing occupational heat stress because it integrates the effects of air temperature, humidity, solar radiation, and wind speed [12], [13], [14]. When WBGT levels exceed the recommended thresholds, typically 28°C-32°C for moderate workloads, workers experience increased physiological strain and reduced capacity for safe, sustained work [15], [16], [17]. Coastal regions, such as those found in eastern Indonesia, present particularly challenging thermal environments [18], [19], [20]. Persistent humidity levels of 70%-%, combined with strong solar radiation and reflective coral-based ground surfaces, may further amplify heat load, especially during midday working hours [21], [22]. Empirical evidence indicates that rising ambient temperatures have measurable impacts on labor performance and occupational safety across sectors, particularly construction. Productivity has been estimated to decrease by approximately 2% for every 1°C rise in temperature above the safe WBGT threshold, reflecting the combined physiological and cognitive

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burdens of thermal strain on workers [23],[24]. Prolonged exposure to excessive heat not only reduces work efficiency but also increases the risk of heat-related symptoms, including dehydration, dizziness, fatigue, and heat exhaustion. In developing tropical regions such as Indonesia, where construction activities frequently occur in open, poorly shaded environments, these effects are likely to be intensified by high solar radiation, humidity, and limited access to cooling infrastructure [25],[26]. Therefore, understanding occupational heat exposure in tropical construction settings is essential for developing adaptive management strategies and preventive interventions.

In addition to environmental exposure, individual and behavioral factors may further influence workers' vulnerability to heat stress. Behavioral attributes such as smoking, alcohol consumption, insufficient sleep, and poor hydration practices have been reported to exacerbate thermal strain by disrupting cardiovascular efficiency and impairing evaporative cooling mechanisms [27]. Furthermore, inadequate work rest cycles, the absence of formal acclimatization programs, and emotional stress caused by workplace conflict or fatigue may compound the risk of heat-related disorders. These factors suggest that heat stress in construction is not only an environmental issue but also a multidimensional occupational safety problem involving physiological, behavioral, and organizational dimensions.

Despite the growing body of literature on occupational heat stress in construction, several important research gaps remain. First, most previous studies have focused on urban tropical environments or large-scale construction projects, while empirical evidence from semi-arid coastal regions, particularly in eastern Indonesia, remains limited [28]. Second, existing studies commonly emphasize environmental heat exposure through WBGT assessment. Still, fewer studies integrate WBGT-based thermal risk with worker-level behavioral and physiological factors such as smoking habits, sleep duration, hydration practices, body mass index, and acclimatization status [29], [30]. Third, although construction workers are recognized as a high-risk group for occupational heat stress, relatively few studies have specifically examined differences between local or native and non-local or migrant workers. This distinction is important because acclimatization, cultural background, communication barriers, work experience, and heat-risk perception may influence heat tolerance, preventive behavior, and vulnerability to heat-related illness [31], [32], [33]. Therefore, context-specific evidence is needed to understand better how environmental, behavioral, physiological, and acclimatization-related factors interact to shape heat-stress risks among construction workers in semi-arid coastal settings.

Given these interrelated risk dimensions, this study investigates the thermal environment and associated heat-stress risks at active construction sites in the coastal region of Sumba Island, Indonesia. Specifically, this study aims to analyze WBGT-based thermal risk levels and identify behavioral and physiological factors contributing to heat-related illness among construction workers. By integrating environmental heat-risk assessment with worker-level data, this study provides context-specific insights into occupational heat resilience. It contributes to the development of adaptive safety strategies for construction projects in tropical semi-arid coastal climates.

2. Materials and Methods

2.1. Study Area

The study area is located in East Sumba, a coastal region in eastern Indonesia characterized by semi-arid climatic conditions and high solar radiation exposure throughout most of the year [2][34][35][36]. The region's physical landscape is dominated by coastal lowlands, dry savanna ecosystems, and coral-based soils, with sparse vegetation and year-round high solar exposure. These environmental features make the area highly susceptible to thermal extremes and heat stress conditions.

The study area was selected based on the results of a Land Surface Temperature (LST) analysis using satellite-derived thermal imagery for the period 2021–2025. This preliminary spatial assessment aimed to identify the hottest surface zones as the basis for site selection in the subsequent field investigation.

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The LST analysis revealed a distinct spatial pattern of surface temperature distribution across East Sumba. The red zones in the thermal imagery consistently corresponded to coastal areas along the northern shoreline, indicating elevated surface heat accumulation. The maximum surface temperature recorded in these zones reached approximately 36,50°C (See Figure 1.), highlighting significant thermal intensity across the coastal environment.

The results of the LST analysis indicate that coastal areas in East Sumba exhibit the highest surface temperatures, primarily due to coral-dominated terrain, sparse vegetation, and strong solar radiation, which intensify local heat accumulation and microclimatic stress. Based on these findings, field measurements using the Wet Bulb Globe Temperature (WBGT) index were conducted to assess thermal exposure and heat-stress risk among construction workers in coastal zones. This approach allows for a direct evaluation of the climatic and occupational heat risk conditions characteristic of East Sumba's semi-arid tropical environment.

The study focuses on East Sumba Regency, East Nusa Tenggara Province, Indonesia (10° S, 120° E), characterized by high solar exposure and moderate humidity. Climatic data were collected from the nearest BMKG station and include monthly averages of Dry-bulb temperature (Tdb, °C), Relative humidity (RH, %), and global horizontal radiation (GHR, W/m²). Meteorological data used in this study were derived from the Typical Meteorological dataset (2009–2023) provided by Climate.OneBuilding.Org. The dataset comprises long-term hourly climate data derived from satellite and ground-based observations under the World Meteorological Organization (WMO) framework. Data for Waingapu–Kunda Airport (Station ID 973400) were extracted to represent the climatic condition of East Sumba [37].

2.2. Data Collection

2.2.1. Microclimate Environmental Measurements

Wet Bulb Globe Temperature (WBGT) is a measure that accounts for four key components of the thermal environment: temperature, humidity, wind velocity, and solar radiation (Budd, 2008). Given the limited climatological data in East Sumba, the study focuses exclusively on two thermal parameters: temperature and humidity. Wind speed is a key variable in the Wet Bulb Globe Temperature method, as it significantly affects the surrounding air temperature [39]. In this study, wind speed is not considered, as air temperature data are available, whereas solar radiation is approximated using an equation based on temperature and humidity. The Wet Bulb Globe Temperature (WBGT, °C) is determined based on three key environmental parameters, which are combined according to the following equation [29], [40]

$$WBGT = 0{,}7Twb + 0{,}2Tbg + 0{,}1Tdb \quad (1)$$

Where *Twb* is natural Wet Bulb Thermometer temperature (℃), *Tbg* is Black globe temperature (℃), and Tdb is 2 m air temperature (dry bulb temperature ℃). Although air temperature at 2 meters is relatively easy to measure, data from globe wet-bulb thermometers are often limited or infrequently recorded [38].

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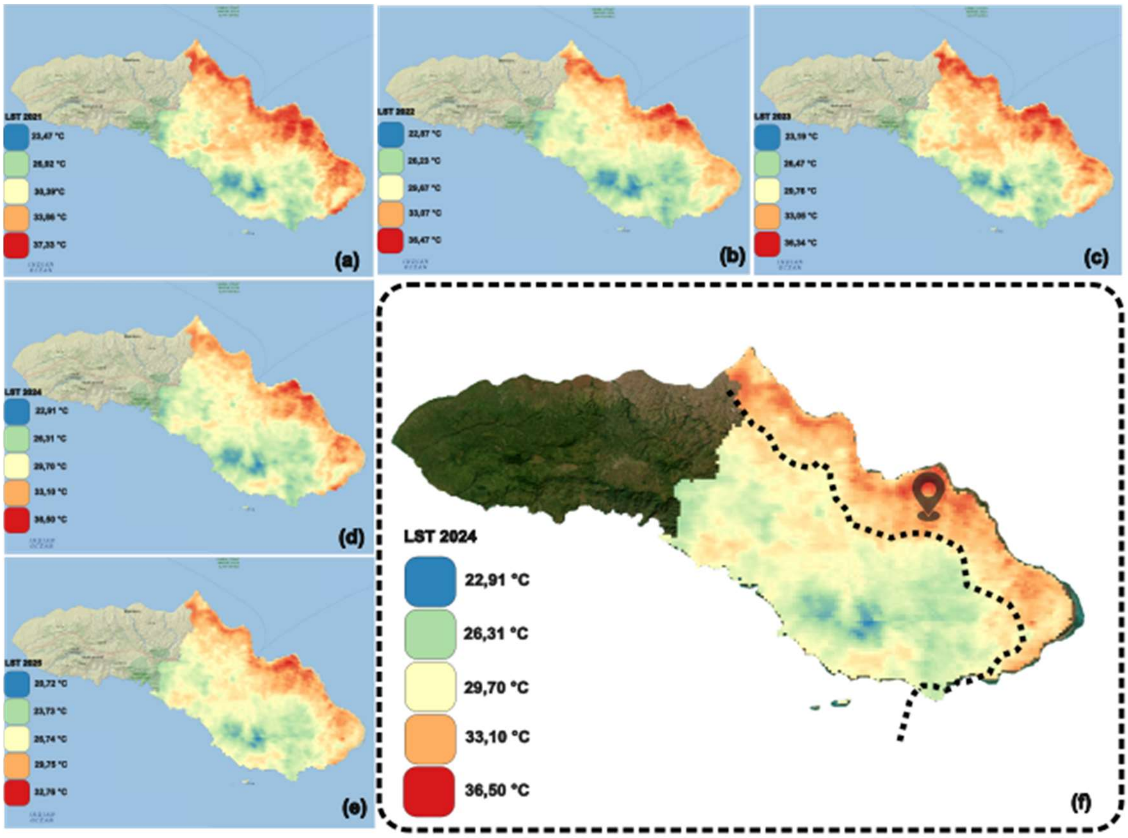

Figure 1. Spatial distribution of Land Surface Temperature (LST) in East Sumba from 2021 to 2025, illustrating consistent thermal concentration in the northern coastal zone.

The wet-bulb temperature (*Twb*) was estimated empirically using the following equation, which relates air temperature and relative humidity under steady-state psychrometric conditions [41]

$$RH = 100 - \frac{300(Ta - Twb)}{Ta} \quad (2)$$

$$Twb = \frac{200Ta + RHTa}{300} \quad (3)$$

In this formulation, RH denotes relative humidity (%), Twb represents wet-bulb temperature (°C), and Ta denotes ambient air temperature (°C). The black globe temperature (*Tbg*), which accounts for the radiative heat load, was subsequently estimated using the following equation [42], [43].

$$Tbg = 1{,}22Tdb - 0{,}045RH + 0{,}0253Q \quad (4)$$

In this context, Q denotes the solar radiation intensity (W/m²). Solar radiation was estimated using the following empirical relationship [44].

2.2.2. Worker Survey

Information on risk perception and intervention effectiveness was obtained through three instruments: data sheets for construction workers, questionnaires and interview guides for managerial staff, and site observation checklists. The questionnaire items were developed based on key literature and existing guidelines on heat stress, including the established heat stress management guidelines

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[15][45][46]. The instruments and equipment used to collect environmental and physiological data are presented in Table 1.

Table 1. Instruments for collecting environmental and physiological data

	Measured Variable	**Equipment / Instrument**	**Manufactur**	**Reference**
1	Dry bulb temp.	-	*Climate.OneBuilding.Org.*	[37]
2	Wet bulb temp.	-	*Climate.OneBuilding.Org.*	[37]
3	Globe temp.	-	*Climate.OneBuilding.Org.*	[37]
4	Relative Humidity	-	*Climate.OneBuilding.Org.*	[37]
5	Air Velocity	-	*Climate.OneBuilding.Org.*	[37]
6	Skin Temp. (Chest)	Temperature Data Logger	*Yuwell*	
7	Fitness (BMI)	-	*Self made*	
8	Body height	Metre stick		
9	Body weight			
10	Sleep quality	How sleep quality (night : 1 - bad; 2 - OK; 3 - good)		
11	Smoking	Self report (1-No; 2- a little; 3 – Yes)		
12	Alcohol drinking	Self report (1-No; 2- a little; 3 – Yes)		

2.2.3. Instrument Validation Procedure

The research instruments were validated before the main field survey to ensure their relevance, clarity, and applicability in the construction context. The validation process included content review, field readability assessment, pilot testing, and consistency checking. The questionnaire items were developed from previous studies. They established heat-stress management guidelines, covering heat-risk perception, behavioral and physiological responses, hydration practices, sleep quality, smoking habits, alcohol consumption, and perceived effectiveness of preventive interventions. Each item was reviewed to ensure its alignment with the study objectives and suitability for construction workers in East Sumba.

A preliminary pilot assessment was conducted to evaluate the clarity of the questionnaire, the suitability of response scales, and the time required for completion. Feedback from this stage was used to revise unclear or repetitive items. The semi-structured interview guide and observation checklist were also reviewed to ensure consistency with the questionnaire indicators. The interview guide was designed to explore workers' experiences, adaptation practices, and perceived heat-related symptoms. At the same time, the observation checklist was used to verify field conditions, including shaded rest areas, access to hydration, PPE use, and work-rest practices.

For Likert-type questionnaire items, internal consistency was examined to ensure that the items within each dimension measured the same construct, particularly heat-stress risk perception, behavioral and physiological responses, and perceived effectiveness of intervention and prevention measures. Environmental and physiological measurements were standardized by applying the same data recording procedures across all sites. Climatic data from Climate.OneBuilding.Org were processed using consistent WBGT estimation equations. In contrast, worker-level data, including

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body temperature, height, weight, BMI, sleep quality, smoking status, and alcohol consumption, were recorded using standardized forms.

2.2.4. Sampling

Data sampling was conducted using a stratified approach based on two criteria: worker origin and occupation. The first criterion distinguished between local workers, defined as workers indigenous to Sumba, and non-local workers, defined as workers originating from outside Sumba. This distinction was used because differences in climatic background, acclimatization, and familiarity with local environmental conditions may influence heat stress vulnerability and risk perception. The second criterion covered major construction occupations considered highly susceptible to heat stress, including steel fixers, carpenters, concrete workers, masons, plasterers, welders, scaffolders, mechanical and electrical workers, demolition workers, and other relevant occupations identified by site managers or project managers. Occupational stratification was applied because these jobs differ in physical workload, outdoor exposure duration, metabolic heat production, use of personal protective equipment, and proximity to heat-generating activities. Thus, the stratified sampling approach was intended to capture workers with different levels of exposure, adaptation, and vulnerability to heat stress in tropical semi-arid construction environments.

2.2.5. Data Collection Protocol

A specific limitation of climatic heat-stress research is that the data-collection period is restricted to hot-weather days within a single season; in Sumba, this typically spans 3 - 6 months, excluding days with heavy rainfall. To address this, a two-day protocol was developed to guide data collection (see Table 2 for details). At each construction site, a team of 6 to 12 workers was recruited. Over two consecutive workdays, research assistants conducted two sessions with the workers, one before and one after work, while the participants continued their regular tasks in between. The interview sessions were intentionally kept informal by avoiding the use of video and audio recording equipment. The sampling stages follow the Work Breakdown Structure (WBS) based on the schedule of work implementation stages.

Table 2. Data Collection Protocol

	Work session	Day Time	After work
Day 1	**Introduction** (Age, Trade, gender, activity, Hydration, Critical incident, Skin Temp., etc)	Continuous recording at work place	Interviews Worker
Day 1	**Night (Rest Activity)** (height, weight, fitness, etc)	*Workers fill out questionnaires at home after work*	Personal baseline data
Day 2	**Collect Completed Questionnaires and interviews** (Sleep Quality, Alcoholic, smoker, etc)	Continuous Report and recording	Semi Structure Interview

2.3. Analysis Method

The data analysis was conducted in three stages. First, the calculated Wet Bulb Globe Temperature (WBGT) values served as the basis for assessing thermal stress risk at the construction

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site. The WBGT index integrates the combined effects of air temperature, humidity, solar radiation, and wind, thus providing a comprehensive measure of heat exposure affecting workers.

Second, an independent-samples t-test was applied to the questionnaire responses to identify significant differences in perceptions between managers and workers across the two main ethnic groups (local Sumbanese and non-local workers) and between age categories (below and above 50 years). Demographic and physiological variables, including body surface area-to-mass ratio, body mass index (BMI), physical fitness, blood pressure, blood glucose, age, smoking habits, sleep quality, and effective heat risk, were further examined using deviation analysis [47], [48], [49], [50] to detect values outside the normal range.

In the third stage, multiple data sources were integrated to construct individual worker cases, combining cross-validated information from physiological measurements, self-reported data, peer reports, manager interviews, environmental records, and on-site observations. These cases were then analyzed using a grounded theory approach [51] to generate a theoretical model explaining risks, consequences, intervention strategies, and their interrelationships in the construction management context.

3. Results and Discussions

3.1. Climatic Data Characteristics

The climatic data employed for calculating the Wet Bulb Globe Temperature (WBGT) index were sourced from the *Climate.OneBuilding.Org* [37] records, hich compiles long-term meteorological observations, including monthly averages of ambient air temperature and relative humidity. These variables constituted the core inputs for estimating thermal stress intensity and characterizing heat exposure conditions within the investigated region.

Following WBGT estimation, a comprehensive climatic assessment was conducted using *Climate Consultant* software to interpret the site's thermal profile and environmental dynamics. This stage enabled a more refined understanding of how local climatic parameters influence human comfort and outdoor thermal conditions. The analytical outcomes, summarized in Table 3, provide an overview of temperature variability, humidity distribution, and seasonal tendencies relevant to thermal comfort evaluation. Collectively, these findings establish the empirical foundation for subsequent analysis on climatic adaptability and inform design strategies responsive to local environmental constraints.

East Sumba exhibits a semi-arid tropical climate characterized by distinct dry and wet seasons. The mean monthly air temperature ranges from 25°C to 28°C, while relative humidity fluctuates between 70% and 85%.

Table 3. Weather Data Summary

WEATHER DATA SUMMARY	**Location: Wangingapu-Kunda.AP-Mau.Hau.AP, NU, IDN**												
	9.6697 South, 120.2997 East, Time Zone From Greenwich 8												
MONTHLY MEANS	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	
Global Horiz Radiation (Avg Hourly)	435	460	505	495	495	447	461	515	564	585	561	483	Wh/Sq.m
Direct Normal Radiation (Avg Hourly)	356	425	505	520	516	531	526	570	600	627	579	452	Wh/Sq.m
Diffuse Radiation (Avg Hourly)	166	139	133	112	106	100	103	103	106	101	114	149	Wh/Sq.m
Global Horiz Radiation (Max Hourly)	973	1056	996	979	870	817	841	970	1020	1036	1023	982	Wh/Sq.m

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WEATHER DATA SUMMARY	Location: Wangingapu-Kunda.AP-Mau.Hau.AP, NU, IDN												
	9.6697 South, 120.2997 East, Time Zone From Greenwich 8												
MONTHLY MEANS	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	
Direct Normal Radiation (Max Hourly)	859	951	935	892	874	840	854	900	930	936	938	982	Wh/Sq.m
Diffuse Radiation (Max Hourly)	414	345	403	291	284	213	299	201	231	225	317	395	Wh/Sq.m
Global Horiz Radiation (Avg Daily Total)	5438	5673	6087	5837	5279	5122	5306	6031	6746	7161	6982	6074	Wh/Sq.m
Direct Normal Radiation (Avg Daily Total)	4449	5239	6085	6134	5967	6085	6049	6669	7175	7674	7209	5682	Wh/Sq.m
Diffuse Radiation (Avg Daily Total)	2079	1717	1606	1323	1230	1155	1192	1213	1269	1245	1426	1881	Wh/Sq.m
Global Horiz Illumination (Avg Hourly)	47594	49764	55381	55406	51419	50221	51453	56770	61333	63361	61943	54060	lux
Direct Normal Illumination (Avg Hourly)	27359	32451	41558	51769	52256	55912	57234	59947	59336	58779	52621	36888	lux
Dry Bulb Temperature (Avg Monthly)	27	27	27	27	27	26	25	25	27	27	28	28	Degrees C
Dew Point Temperature (Avg Monthly)	23	23	24	23	22	21	19	20	21	22	23	25	Degrees C
Relative Humidity (Avg Monthly)	79	82	82	81	75	73	72	71	70	73	75	85	percent
Wind Direction (Monthly Mode)	300	290	290	110	120	110	110	120	100	90	220	210	Degress
Wind Speed (Avg Monthly)	2	1	2	2	2	3	3	2	3	3	3	2	m/s
Ground Temperature (Avg of 3 Depths)	27	27	28	27	27	26	25	25	26	26	27	27	Degrees C

Notes: Data Source SCR-TMYx 973400 WMO Station, Number Elevation 12 m
Source: Analysis by Author, calculated using Software Climate Consultant, based on TMYx data.

The climatic profile indicates that heat exposure in East Sumba is not driven solely by high air temperature, but by the combined influence of humidity, solar radiation, and limited thermal relief throughout the day. Although the monthly mean dry-bulb temperature appears relatively stable, ranging from

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approximately 25°C to 28°C, the persistently high relative humidity reduces the body's ability to dissipate heat through evaporative cooling. This condition is particularly important for construction workers, whose metabolic heat production increases during physically demanding tasks. Therefore, the relatively narrow monthly temperature range should not be interpreted as a low-risk condition. Instead, the combination of sustained humidity, high radiation intensity, and outdoor work activities creates a thermal environment in which heat strain may progressively accumulate over the workday.

3.2. WBGT Estimation and Heat Stress Risk Classification

The Wet Bulb Globe Temperature (WBGT) index can be estimated using the following empirical formulation $WBGT = 0,7T_{wb} + 0,2T_{bg} + 0,1T_{db}$, where Twb represents the natural wet-bulb temperature, Tbg denotes the black globe temperature, and Tdb refers to the dry-bulb air temperature. This equation accounts for the combined effects of air temperature, humidity, and solar radiation to quantify thermal stress in outdoor environments.

The results indicate a distinct seasonal variation in WBGT values across the study area. Elevated WBGT levels were observed from January to May, reflecting the combined influence of high air temperatures and humidity typical of the late wet season. During the June to August interval, WBGT values decreased to a moderate range, coinciding with lower humidity and relatively milder air temperatures. However, from September to December, the WBGT index increased again, marking another period of high heat-exposure risk as temperatures and humidity rose toward the onset of the wet season.

Table 4. WBGT Data Summary

Monthly	Tdb (°C)	RH (%)	GHR (W/m2)	Twb (°C)	Tbg (°C)	WBGT (°C)	Category
JAN	27	79	435	25,11	40,39	28,36	**High Risk**
FEB	27	82	460	25,38	40,89	28,64	**High Risk**
MAR	27	82	505	25,38	42,03	28,87	**High Risk**
APR	27	81	495	25,29	41,82	28,77	**High Risk**
MAY	27	75	456	24,75	41,10	28,25	**High Risk**
JUN	26	73	447	23,66	39,74	27,11	**Moderate**
JUL	25	72	461	22,67	38,92	26,15	**Moderate**
AUG	25	71	515	22,58	40,33	26,38	**Moderate**
SEP	27	70	564	24,30	44,06	28,52	**High Risk**
OCT	27	73	585	24,57	44,46	28,79	**High Risk**
NOV	28	75	561	25,67	44,98	29,76	**High Risk**
DEC	28	85	483	26,60	42,55	29,93	**High Risk**

The WBGT pattern suggests that heat-stress risk in East Sumba follows a seasonal yet persistent pattern. High-risk conditions from January to May and again from September to December indicate that heat exposure is not limited to a short extreme-weather period, but extends across most of the construction calendar. This has important implications for project planning because outdoor construction activities are commonly scheduled year-round. The decrease in WBGT values from June to August may reduce the intensity of heat stress. Still, it does not eliminate the need for preventive control, particularly for workers performing heavy tasks or wearing personal protective equipment. Thus, WBGT should be used not only as a descriptive climatic indicator but also as an operational tool for determining safe work duration, rest frequency, and hydration requirements.

To better understand the implications of the WBGT results, the calculated index values were compared with international standards of heat stress risk classification. According to [15], [52], [53], [54], WBGT thresholds can be interpreted as follows :

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Table 5. WBGT Analysis and Risk Description

Risk Category	WBGT Range (°C)	Risk Description	Implications
Low Risk	< 25.0	Minimal thermal strain under normal activity levels.	Suitable for general outdoor work with standard hydration and rest intervals.
Moderate Risk	25.0 – 28.0	Noticeable heat stress may occur during prolonged or intensive activity.	Requires rest breaks, hydration monitoring, and shaded rest areas.
High Risk	28.1 – 31.0	High probability of heat strain; unsafe for continuous work without protective measures.	Demands reduced work duration, frequent rest, and environmental monitoring.
Extreme Risk	> 31.0	Very high heat stress; potential for heat-related illnesses.	Work should be restricted to critical tasks only with strict safety control.

Methodological limitations of WBGT estimation. Although the WBGT index provides a useful basis for classifying occupational heat-stress risk, the WBGT values in this study were estimated without direct field measurement of wind speed. The calculation was based mainly on available climatic parameters, including dry-bulb temperature, relative humidity, and solar radiation, while air movement was not directly incorporated through on-site anemometer measurements. This limitation may affect the precision of the risk thresholds presented in Table 5, as wind speed influences convective and evaporative heat exchange between the worker's body and the surrounding environment. Lower air movement may increase the effective heat burden, while stronger wind may reduce perceived thermal stress through enhanced cooling. Therefore, the WBGT risk categories in this study should be interpreted as indicative screening thresholds rather than absolute exposure limits. Future studies should validate the estimated WBGT values through direct field measurements using calibrated WBGT meters, globe thermometers, natural wet-bulb sensors, and anemometers across different construction sites, work periods, and coastal microclimatic conditions in East Sumba.

Overall, the results demonstrate that East Sumba's climatic conditions pose significant challenges in maintaining thermal comfort and safety.

The comfort zone (Figure 2), shaded in gray on the chart, represents conditions in which thermal neutrality is generally achieved without active cooling or heating. However, the data show that both the dry-bulb and wet-bulb temperature curves consistently exceed this range during most months, particularly from January to May and September to December. This implies that thermal discomfort and heat stress are likely to occur during prolonged outdoor activities or in unconditioned indoor spaces.

The pattern aligns closely with the seasonal distribution of WBGT values, where elevated air temperature and humidity contribute to higher WBGT indices. As previously calculated, WBGT levels during the high-temperature periods fall within the "Moderate to High Risk" category under [15], [52], [53], and [54]. The high solar radiation levels (800–1000 Wh/m²) observed in the same months further exacerbate heat load on the human body, increasing the potential for thermal strain and dehydration.

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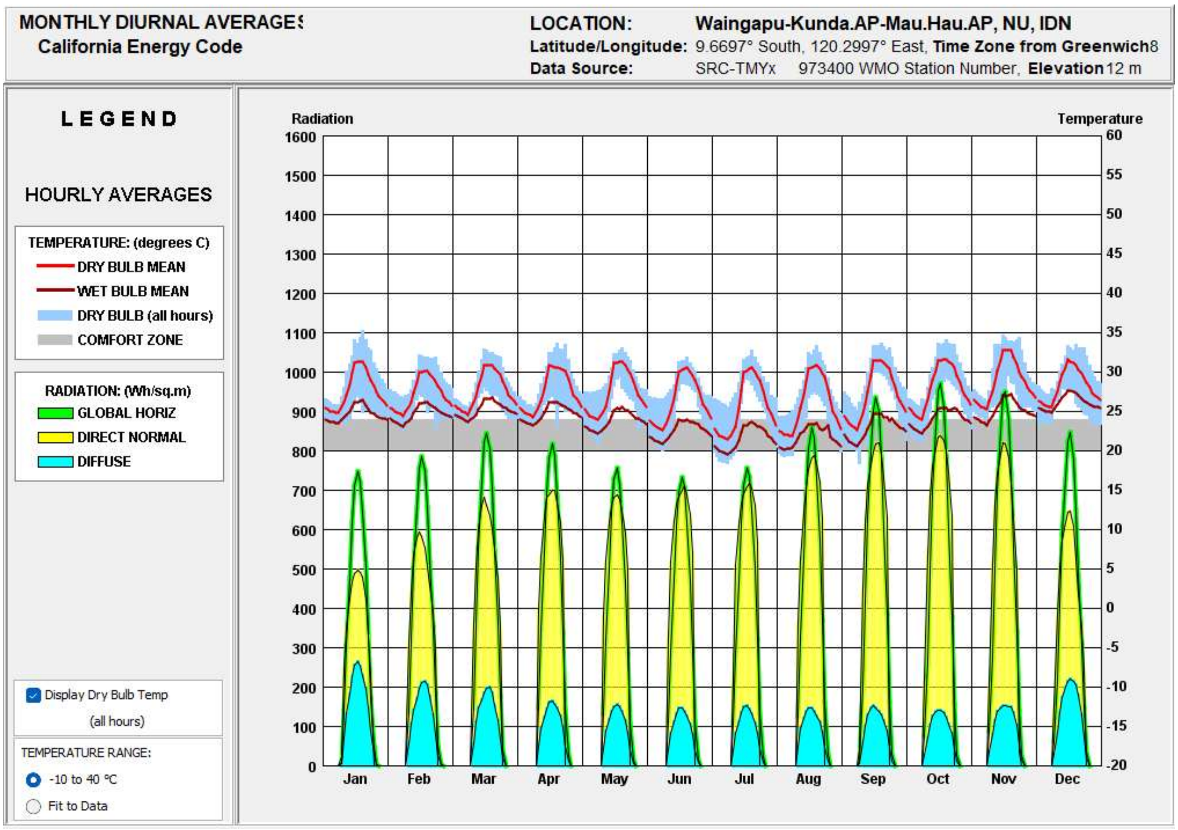

Figure 2. Monthly diurnal averages of dry-bulb temperature, wet-bulb temperature, and solar radiation in Waingapu–Kunda, East Sumba.
Source: Analysis by Author, Using Software Climate Consultant [55]

3.3. Thermal Risk Assessment

Based on the correlation between the climatic parameters and WBGT classification, thermal risk in East Sumba exhibits a bimodal pattern:

High Risk Periods (January–May and September–December):

During these months, WBGT values typically exceed 28°C, placing outdoor workers in the High Risk category. This condition is associated with elevated direct and global solar radiation peaks and high humidity, leading to intense heat stress, especially during midday. Prolonged exposure without adequate rest, hydration, or shading can lead to heat exhaustion or heat stroke.

Moderate Risk Period (June–August):

During this relatively cooler and drier period, WBGT values range from 25°C to 27°C, corresponding to the Moderate Risk category. While thermal discomfort may persist, environmental heat load is reduced, and the risk of severe heat stress decreases. Nevertheless, preventive measures such as controlled work-rest cycles remain essential.

Overall, the analysis confirms that East Sumba's climatic regime imposes persistent thermal stress throughout most of the year, driven by high solar radiation and limited diurnal temperature variation. The results highlight the need for adaptive environmental design—including passive ventilation, shading devices, and reflective materials—to mitigate heat exposure. In occupational settings, implementing heat-stress management protocols based on WBGT monitoring is crucial to safeguard worker health and productivity.

3.3.1. Obtained Sample

An independent-samples t-test was used to examine differences in perceived heat-related risk factors between two main respondent groups: local workers native to East Sumba and non-local workers who had migrated from other regions. Field observations were conducted from 2023 to 2024

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at eight active construction sites across East Sumba. These included 4 new building projects focusing on structural works from foundation to Upper Structure, 2 finishing projects, 1 road asphalting project, and 1 drainage project. 2 interior projects were initially planned for inclusion; however, they were later omitted because sample saturation had been achieved and the indoor conditions—equipped with air-conditioning—were not considered thermally challenging.

The final dataset comprised 78 respondents across 10 occupational categories, including steel fixers, carpenters, concrete workers, masons, plasterers, welders, scaffolders, mechanical and electrical workers, demolition workers, and several other trades considered highly exposed to heat stress. Descriptive statistics summarizing the characteristics of the worker sample are presented in Table 6.

Table 6. Characteristics of workers sample

Item	Variables	N	Mean	Range and percentages
	General			
1	Age (years)	78	39,02	20-59
2	Work Duration (Hours)	78	> 7	4-8
3	Type of work	78		
4	PPE (*APD*)	78		
	Heat Stress Risk Perception			
5	Heat Perception	78	2,92	1 – 5 (Positive Scale)
6	Decreased Concentration	78	3,19	1 – 5 (Positive Scale)
7	Awareness of Heat	78	2,72	1 – 5 (Positive Scale)
8	Understanding of Heat Stress	78	3,05	1 – 5 (Positive Scale)
9	Perception of Heat Risk	78	2,91	1 – 5 (Positive Scale)
	Behavioral & Physiological responses			
10	Sweating Frequently	78	2,94	1 – 5 (Positive Scale)
11	Persistent Thirst	78	2,91	1 – 5 (Positive Scale)
12	Dizziness or Muscle Cramps	78	3,15	1 – 5 (Positive Scale)
13	Resting During Heat Exposure	78	3,13	1 – 5 (Positive Scale)
14	Stopping Work Due to Extreme Heat	78	2,73	1 – 5 (Positive Scale)
	Perception of Intervention and Prevention Effectiveness			
15	Shaded rest area	78	3,21	1 – 5 (Positive Scale)
16	Availability of Drinking Water	78	3,13	1 – 5 (Positive Scale)
17	Work-Rest Schedule	78	2,71	1 – 5 (Positive Scale)
18	Supervisor Monitoring	78	3,35	1 – 5 (Positive Scale)
19	Heat Stress Training	78	2,82	1 – 5 (Positive Scale)
20	Adequate Preventive Measures	78	3,01	1 – 5 (Positive Scale)
	Measurements			
21	Body Height (m)	78	1,67	
22	Body Weight (kg)	78	64,93	
23	BMI	78	23,41	
24	Body Temp. (◦C)	78	36,50	
25	Helmet Temp. (◦C)	78	38,36	
26	Smoking Habit	78		(43.59% No, 56.41% Yes)
27	Alcohol Consumption	78		(38.46% No, 23.08% Yes, 38.46% Sometimes)

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3.3.2. Critical incident analysis

Based on the model's results, individual cases of workers who reported heat-related health problems were analyzed to identify patterns in perceived risk. Among the 78 construction workers (40 non-local and 38 local from East Sumba) who participated in the interviews, 15 reported experiencing health problems from heat exposure while working outdoors. Of these, 10 cases were reported among non-local workers and 5 among local workers. The actual working hours of construction projects in East Sumba generally ranged from 08:00 to 16:00, following the regular daily work schedule at the observed sites. However, during this working period, the interval between 11:00 and 15:00 was the most critical exposure window, as it coincided with peak WBGT conditions and the highest potential for heat stress among outdoor construction workers. Therefore, although construction activities were not conducted throughout the entire day, a substantial portion of the working schedule overlapped with the most hazardous thermal period.

The reported symptoms included high body temperature or fever (4 cases), feeling very thirsty (3 cases), feeling dizzy or lightheaded (3 cases), shortness of breath (1 case), nausea or vomiting (2 cases), and fainting or loss of consciousness (2 cases). The timing and frequency of these incidents are presented in Figure 3, which shows how heat-related symptoms varied across different periods of work exposure.

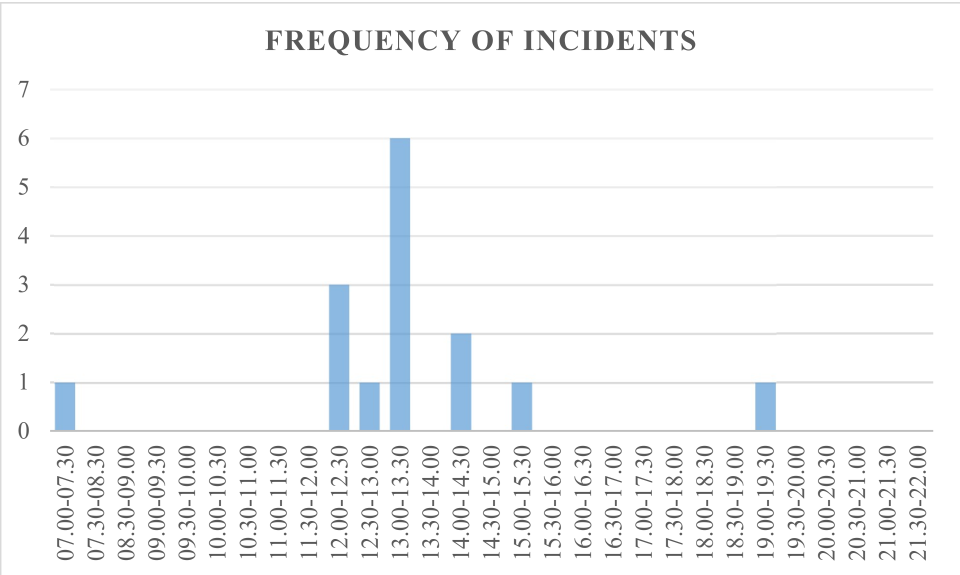

Figure 3. Temporal pattern of the frequency of heat incidents on site

Based on the recorded frequency of heat-stress incidents in East Sumba, a total of 15 cases (19.2%) were identified, with 10 incidents occurring between 12:00 and 14:00, coinciding with the period of highest ambient temperatures. This pattern aligns with the WBGT measurements, which indicate a High-Risk category during January to April, when thermal exposure is typically most intense. The 19.2% incidence rate should be considered substantial because it represents reported heat-related health problems among active construction workers rather than a general perception of discomfort. This means that nearly one in five workers had already experienced symptoms such as fever, thirst, dizziness, nausea, or fainting during outdoor construction work. The urgency of intervention is supported by regional evidence from Southeast Asia. Singapore's Ministry of Manpower, for example, requires outdoor workplaces to implement WBGT-based controls, including acclimatisation, regular drinking water, shaded rest, hourly WBGT monitoring during hotter periods, and mandatory rest breaks for heavy work at higher WBGT levels [56]. In Thailand, studies on occupational heat standards have also emphasized that WBGT-based limits need to be

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evaluated under warming climatic conditions, particularly for physically demanding work such as construction [57].

Furthermore, a meta-analysis of construction workers reported that 60% of workers exposed to elevated heat experienced productivity loss, with greater effects when WBGT exceeded 28°C [58]. Since the WBGT values in East Sumba exceeded 28°C during most high-risk months, the observed 19.2% incident rate provides field-based evidence that climatic heat exposure has already translated into worker health impacts. These findings justify immediate preventive measures, particularly midday work-rest regulation, shaded recovery areas, hydration programs, worker acclimatisation, and active supervision.

In addition, one case of dizziness was reported between 07:00 and 07:30, which was likely influenced by insufficient sleep during the preceding night and a low body mass index (BMI) underweight status. These findings suggest that both environmental heat intensity and individual physiological conditions contribute to heat-related symptoms among construction workers in the region.

The statistical analysis revealed notable differences in perception between local and non-local workers across several thermal risk indicators. The t-test results demonstrated variation in: Heat Risk stress Perception (t = –0.289, p = 0.774), Behavioral & Physiological responses (t = 1.032, p = 0.2338), Perception of the Effectiveness of interventions & Preventive (t =- 0.352, p = 0.726).

Independent Samples T-Test

		Statistic	df	p		Effect Size
Heat Risk stress Risk Perception	**Student's t**	-0.289	76.0	0.774	Cohen's d	-0.0654
Behavioral & Physiological responeses	**Student's t**	1.032	76.0	0.305	Cohen's d	0.2338
Perception of the Effectiveness of Interventions and Preventive	**Student's t**	-0.352	76.0	0.726	Cohen's d	-0.0798

Note. H_a $\mu_{\text{Sumba Timur}} \neq \mu_{\text{Out-of-region worker}}$

Figure 4. Independent samples T-Tes Local Worker and Out of Region Worker

For Heat-Stress Risk Perception, local workers reported a mean score of 2.94 (SD = 0.592), while out-of-region workers had a slightly higher mean of 2.98 (SD = 0.719). This suggests that both groups perceived a comparable level of heat-stress risk, with marginally greater awareness among out-of-region workers. The t-test result (t(76) = –0.289, p = 0.774) confirmed that this difference was not statistically significant, and the effect size (Cohen's d = –0.065) indicated a negligible magnitude.

The absence of statistically significant differences between local and non-local workers should not be interpreted as the absence of vulnerability. Rather, it suggests that both groups are exposed to similar site-level heat hazards and may share comparable perceptions of heat risk because they work under the same environmental and organizational conditions. However, the slightly higher behavioral and physiological response scores among local workers indicate a possible practical difference in adaptation. Local workers may have developed informal coping strategies through long-term exposure to East Sumba's climate, such as adjusting work pace, seeking shade more frequently, or tolerating thermal discomfort more effectively. In contrast, non-local workers may recognize the risk but may not yet possess the same level of physiological acclimatization or behavioral adaptation. This distinction is important because risk perception does not always correspond directly to heat tolerance.

In contrast, the Behavioral and Physiological Responses dimension showed a reversed pattern. The mean score for local workers (M = 3.05, SD = 0.653) was slightly higher than that of out-of-region workers (M = 2.90, SD = 0.608), suggesting that local workers demonstrated somewhat stronger physiological or behavioral adaptation to hot working conditions. However, the difference

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was not statistically significant (t(76) = 1.032, p = 0.305, d = 0.234), though the effect size indicated a small practical difference.

Group Descriptives

	Group	N	Mean	Median	SD	SE
Heat Risk stress Risk Perception	**Sumba Timur**	38	2.94	2.90	0.592	0.0960
	Out-of-region worker	40	2.98	3.00	0.719	0.1136
Behavioral & Physiological responeses	**Sumba Timur**	38	3.05	3.00	0.653	0.1060
	Out-of-region worker	40	2.90	2.80	0.608	0.0961
Perception of the Effectiveness of Interventions and Preventive	**Sumba Timur**	38	3.01	3.00	0.536	0.0870
	Out-of-region worker	40	3.06	3.17	0.598	0.0945

Figure 5. Group Descriptives: Local Worker and Out-of-Region Worker

These outcomes suggest that non-local workers were more sensitive to heat stress and humidity, likely due to limited acclimatization to East Sumba's semi-arid climatic conditions. In contrast, local workers appeared to have developed greater environmental resilience through prolonged exposure to the regional thermal environment (See Figure 6).

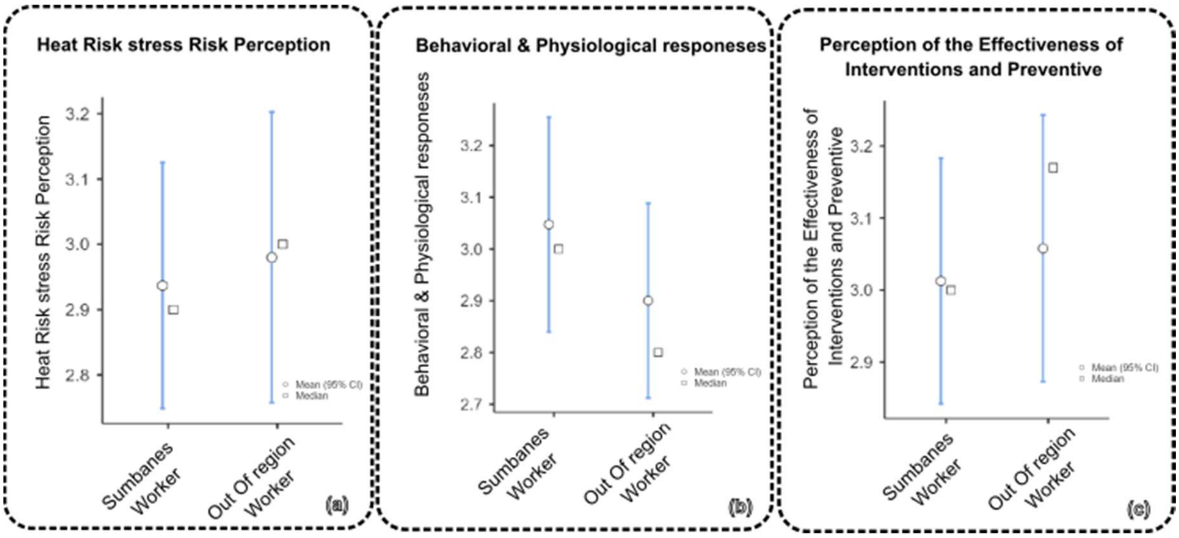

Figure 6. Plots (a) Heat Risk Stress Perception (b) Behavioral & Physiological responses (c) Perception Effectiveness of Interventions & Preventives

When analyzed according to smoking behavior, the group of smokers exhibited a slightly higher proportion of heat-related illness cases (23.26%) compared to non-smokers (14.29%) (see Table 7). This finding suggests that smoking may be associated with a marginal increase in vulnerability to heat stress during outdoor work. The physiological effects of smoking—such as reduced cardiovascular efficiency and impaired thermoregulation—could contribute to decreased tolerance to elevated temperatures, thereby heightening the likelihood of heat-related symptoms among smokers.

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Table 7. Percentage of heat disorder case smoking and non smoking worker

	Whole Sample	
	Smoker	**Non Smoker**
N	43	35
Heat Disorder Cases	10	5
Percentages Of Case	23,26 %	14,29%

In the temperature analysis, a variable difference was observed between body temperature and the temperature inside the safety helmet. Among 20 workers, including welders, operators, steel workers, carpenters, masons, and bricklayers-occupations with a high potential for direct heat exposure-the average temperature difference recorded between body and helmet interior was approximately 1.85 °C. This finding indicates that microclimatic conditions within the helmet may increase workers' thermal load, particularly in occupations involving prolonged exposure to radiant and ambient heat sources. (See table 8).

Table 8. Temperature Record inside the safety helmet

Subject (Trade)	**Body Temperature °C**	**Temperature Record in Safety Helmet °C**	**Difference °C**
Welder, Operator, Steelworker	36,6	37,2	0,6
	36	37,1	1,1
	35,5	40,5	5
	36,1	37,4	1,3
	36,7	38,9	2,2
	36,1	38,9	2,8
	36,4	37,7	1,3
	36,8	39,2	2,4
	36,5	36,9	0,4
Carpenter, Mason, Bricklayer	36,2	38,9	2,7
	36,5	37,7	1,2
	36,9	37,4	0,5
	36,6	37,4	0,8
	36,7	38,5	1,8
	36,1	38,6	2,5
	36,4	37,9	1,5
	36,5	40,4	3,9
	36,5	39,3	2,8
	37,3	38,2	0,9
	36,6	37,8	1,2

The recorded temperature difference between body temperature and the internal helmet environment suggests that personal protective equipment may impose an additional microclimatic burden on workers. Although helmets are essential for head protection, prolonged use in direct sunlight can trap heat and increase thermal discomfort. This finding highlights a practical dilemma in construction safety: protective equipment reduces the risk of mechanical injury but may also increase the risk of heat strain when used in hot outdoor environments. Therefore, heat-stress management should not be separated from PPE management. Possible interventions include scheduled helmet-off recovery periods in safe shaded areas, improved helmet ventilation, reflective helmet surfaces, and task rotation for workers exposed to intense radiant heat.

3.3.3. Heat Risk Factors at the Worksite

The identified heat-risk factors indicate that heat stress at construction sites resulted from the interaction among environmental, occupational, behavioral, physiological, and organizational conditions. Climatic heat, including high humidity and solar radiation, created the baseline exposure risk. Workplace characteristics, such as open construction areas, reflective ground surfaces, and limited shade, intensified this exposure. At the same time, task-related factors, including heavy

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physical work and prolonged PPE use, increased metabolic and microclimatic heat loads. Individual factors such as smoking, insufficient sleep, alcohol consumption, low BMI, and limited acclimatization further shaped workers' vulnerability. Therefore, heat stress in this context should be understood as a systemic occupational safety issue rather than an isolated environmental problem. (See Table 9)

Table 9. Risk factor identified

Category	Identified Risks	Elaboration
Climatic Heat	Humidity, solar radiant heat	• The project location on Sumba Island experiences high WBGT values from January to May, placing it within the high-risk category for heat exposure.
		• The coastal site has a relative humidity of 70%–80%, which intensifies heat perception and reduces heat dissipation during work.
		• Working hours between 11:00 a.m. and 3:00 p.m. represent the hottest period of the day.
Workplace heat	Open Site Risk	• The open-site environment, characterized by dry savanna and coral-based ground surfaces, increases reflected heat exposure, and occasional fire incidents occur during the dry season.
		• Welders, steelworkers, operators, carpenters, and bricklayers were the most exposed occupations.
Clothing Effect	PPE	• The average temperature difference between body and helmet air was 1.85°C, indicating added heat load.
Metabolic Helth	Sleep deprivation–related workload	• Several workers reported insufficient nighttime sleep due to heat discomfort and poor ventilation.
	Fatigue	• Heat stress cases were linked to poor sleep and underweight BMI conditions.
	Lifestyle personal health	• Smokers showed a higher percentage of heat-related symptoms than non-smokers.
		• Alcohol consumption was associated with sleep disturbances and reduced alertness at work.
Personal Factor	Ethnicity	• Local workers demonstrated better climatic acclimatization than non-local workers, despite the absence of formal acclimatization programs.
		• No formal acclimatization process in place.
	Psychological stress	• Emotional stress from interpersonal conflicts also contributed to increased heat strain.

The risk-factor structure presented in Table 9 suggests that effective intervention should be implemented through layered controls. Environmental and workplace risks require engineering and administrative measures, such as shaded rest areas, improved ventilation, reflective materials, and WBGT-based scheduling. Task-related risks require work rotation and adjustment of heavy activities to cooler periods of the day. Individual risks require worker education, hydration monitoring, awareness of sleep and fatigue, and special attention to non-local or newly arrived workers. This layered approach is more appropriate than relying solely on individual self-regulation because workers may continue working despite heat-related discomfort due to productivity pressure, lack of awareness, or limited authority to stop work.

4. Conclusions

The study demonstrates that construction workers in East Sumba are exposed to persistent thermal stress due to the island's semi-arid tropical climate. The Wet Bulb Globe Temperature

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(WBGT) analysis classified most working months—particularly from January to May as belonging to the high-risk category, corresponding to periods of elevated air temperature and humidity.

Interviews and field measurements indicated that heat-related symptoms such as dizziness, fatigue, excessive sweating, and mild dehydration were commonly reported, particularly during midday, when radiant and ambient heat peaked. Non-local workers, who lacked physiological acclimatization to the local microclimate, were more susceptible to heat-related discomfort than local workers. However, statistical testing revealed no significant difference in their overall risk perception and preventive awareness.

Individual factors, including smoking habits, alcohol consumption, insufficient rest, and underweight BMI, were identified as contributing elements that potentially increase vulnerability to heat stress. Furthermore, the recorded mean temperature difference of 1.85 °C between body temperature and the safety helmet's internal environment indicates an additional microclimatic load that may intensify perceived heat strain during prolonged outdoor activities.

The findings underline the importance of adopting a comprehensive heat management framework in construction operations. Such a framework should include work–rest cycles aligned with WBGT-based thresholds, provision of shaded rest areas, accessible hydration points, and behavioral adaptation programs. Strengthening informal acclimatization practices—especially for non-local workers can enhance thermal resilience and reduce the likelihood of heat-related illnesses in tropical construction settings.

Future research should expand the scope of this study by conducting direct field-based WBGT measurements at construction sites, including wind speed, solar radiation, and real-time microclimatic monitoring. Further studies are also recommended to include larger sample sizes, longer observation periods, and comparative analyses across different climatic regions in Indonesia. In addition, future research may evaluate the effectiveness of specific heat-stress interventions, such as WBGT-based work rest schedules, improved helmet ventilation, shaded recovery areas, and structured acclimatization programs for non-local workers. Such studies would provide stronger evidence to inform the development of practical heat-stress management guidelines in tropical and semi-arid construction environments.

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