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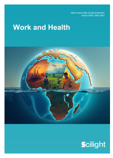

Article

Heat Stress Exposure and Physiological Responses among Sugarcane Workers in Thailand

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Abstract: Introduction: Occupational heat stress can lead to cardiovascular and thermoregulatory changes, including elevated heart rate, increased core temperature, and altered blood pressure. Evidence remains limited regarding the physiological impact of heat stress in tropical occupational settings. Sugarcane workers in Thailand experience prolonged exposure to extreme heat during harvesting. This study assessed the impact of heat stress exposure on physiological responses among Thai sugarcane workers. Methods: Field measurements were conducted in Nakhon Sawan Province during cooler and hotter harvesting periods in 2023. Demographic, health, and work-related data were collected using a questionnaire. Heat stress exposure was assessed using Wet Bulb Globe Temperature (WBGT) across entire shifts, and a full work shift time-weighted average effective WBGT ($WBGT_{eff}$-FS-TWA), adjusted for clothing, was calculated. Resting heart rate, body temperature, and blood pressure were recorded pre- and post-shift. Associations between $WBGT_{eff}$-FS-TWA and post-shift physiological parameters were analysed using general linear regression, adjusting for pre-shift values and confounders. Results: Mean $WBGT_{eff}$-FS-TWA was 31.3 ± 2.8 °C (range: 22.9–35.4 °C). Post-shift systolic and diastolic blood pressures were significantly lower, while heart rate and body temperature were significantly higher compared to pre-shift values ($p < 0.001$). $WBGT_{eff}$-FS-TWA was not associated with post-shift blood pressure. However, heart rate increased by 0.61 beats/min (95% CI: 0.24–0.98) and body temperature by 0.02 °C (95% CI: 0.002–0.03) per 1 °C increase in $WBGT_{eff}$-FS-TWA. Conclusion: Heat stress exposure was linked to modest increases in heart rate and body temperature among sugarcane workers. With rising global temperatures, monitoring cardiovascular and thermoregulatory responses is critical for safeguarding workers in hot environments.

Keywords: heat exposure; wet bulb globe temperature; physiological strain; agricultural workers; harvesting period; global warming

1. Introduction

The rise in global temperatures driven by climate change is a significant concern. Since historical data collection began, the decade from 2013 to 2024 was the warmest on record globally, with 2024 marking the hottest year in history [1]. In Thailand, 2024 was recorded as having the highest average annual temperature in the previous 74 years (1952–2024), with the average annual temperature at 28.5 °C [2].

Sugarcane is a vital crop in Thailand's economy, having an annual cultivation area of over 16 billion square metres during the last 10 years, spanning 47 Thai provinces [3]. In 2023, Thailand's Nakhon Sawan Province had the largest sugarcane cultivation area of any Thai province, at 1.3 billion square metres, with approximately 6.4 million tons of harvested sugarcane sent to sugar mills [3]. The sugarcane harvesting period in Thailand is generally from December to March, spanning Thailand's cool season (mid-October to mid-February) and hot season (mid-February to mid-May) [4].

Sugarcane workers often experience adverse work conditions with heavy workload in extremely hot and humid conditions [5]. We previously showed that Thai sugarcane workers are exposed to high temperatures [6] and that they have a high prevalence of heat related symptoms [7]. There is evidence showing that physiological parameters in Thai sugarcane harvesters i.e., systolic blood pressure, body temperature, and heart rate change during the course of a single work shift [4]. While shift-based physiological changes are documented in Thai sugarcane harvesters, an international gap remains regarding the extent to which heat stress exposure affects physiological parameters within high-humidity tropical climates. This gap is a particular concern in Thai sugarcane harvesters whose heat stress exposure has been found to exceed the standards established by Thailand and the American Conference of Governmental Industrial Hygienists (ACGIH) [4,6,8,9]. Because of the significant increase in global temperatures and the importance of agriculture in Thailand, it is important to assess the extent of heat-induced physiological parameter changes in Thai workers, and more broadly. The situation is particularly urgent for Thai sugarcane workers as they are an informal workforce to which Thai regulatory standards of occupational health and safety are not officially applied [4]. This study aimed to compare physiological parameters between pre-shift and post-shift, and to evaluate the effects of heat stress exposure measured using effective Wet Bulb Globe Temperature (WBGT), on physiological parameter responses (blood pressure, heart rate, and body temperature) among Thai sugarcane workers.

2. Materials and Methods

Details for the study design, setting, period, participant selection, heat stress assessment, and questionnaire have been described previously [6]. This cross-sectional study was conducted on 300 sugarcane workers. Data collection occurred over 14 non-consecutive sampling days during the cooler months and 11 consecutive days during the hotter month of the sugarcane harvesting season. The selection of study days was based on the availability and agreement of both the sugarcane field owners and the participating workers. The research took place in sugarcane fields located in the Phayuha Khiri District, Nakhon Sawan Province, Thailand. Workers from 13 camps (temporary residential settlements for sugarcane harvest workers) in the Khao Kala Sub-district participated in the study. The sugarcane harvesting workforce encompasses several roles, including manual cutting, levelling loaded cane on trucks, counting stalks, tractor driving, and operating leaf-removal machinery. This study specifically recruited participants whose primary task was manual harvesting, which involves cutting stalks with a machete, stripping leaves, and piling stalks in rows. We also included workers who performed these manual tasks in combination with secondary duties, such as levelling or counting.

The WBGT was measured, following ISO 7243:2017 [10], using the TSI Quest, Model: QUESTemp 34 (Calibrated on 9 January 2023). Two QUESTTemps were placed in each field for a full work shift (approximately 06:00 to 17:00). The instruments were calibrated daily by plugging the verification module into the sensor at the top of the unit both before and after measurements. Every 5 min, the QUESTTemps logged the results for natural wet-bulb temperature (Tnwb), dry-bulb temperature (Tdb), globe temperature (Tg), relative humidity (Rh), and measured WBGT. The measured WBGT for outdoor environments, which applies a weighted average of 70% Tnwb, 20% Tg, and 10% Tdb [11], was calculated as:

$$\text{WBGT (outdoor)} = 0.7\ \text{Tnwb} + 0.2\ \text{Tg} + 0.1\ \text{Ta} \quad (1)$$

Subsequently, the effective WBGT was calculated as:

$$\text{Effective WBGT} = \text{the measured WBGT} + \text{Clothing Adjustment Factor (CAF)} \quad (2)$$

According to the ACGIH guidelines, the Clothing Adjustment Factors (CAFs) for a standard cotton shirt and trousers and for double layer cloth (woven) clothing are 0 °C and 3 °C, respectively [11]. The CAF for double layer clothing was applied for the participants wearing three layers of shirt because there is no CAF guideline for more than two layers of clothes. A full work shift time-weighted average effective WBGT ($WBGT_{eff}$-FS-TWA) estimate was determined.

Participants completed a structured questionnaire covering information on demographic characteristics, health behaviours, and working conditions. To ensure data quality and accommodate varying literacy levels, the questionnaire was administered via face-to-face interviews by five trained field representatives during the post-shift period.

For the purpose of this study, "physiological responses" refer to acute (same day) changes in heart rate, blood pressure, and body temperature of the participants, taken in pre-shift and post-shift measurements [4]. Physiological measurements were conducted by five trained field representatives. All representatives underwent standardised training on the proper use of the automatic blood pressure monitors and infrared ear thermometers to ensure data consistency and inter-observer reliability. Resting heart rate and blood pressure (systolic and diastolic) were assessed using an automatic blood pressure monitor (Brand: Omron; Model: HEM 7156; Certification of medical quality: CE0197; Accuracy: ±3 mm Hg for blood pressure and ±5% of reading for heart rate [12]). Left and right tympanic temperatures were assessed using an infrared ear thermometer (Brand: Braun; Model Name: IRT 6520; Measurement distance: Contact; Measurement speed: 1 s; Clinical accuracy: ±0.2 °C [13]). Blood pressure, heart rate, and body temperature measurements were taken three times with a one-minute interval between consecutive reading, and then the average value was calculated from the three readings. Body temperature was calculated from six readings, three from the left and right tympanic temperatures. To maintain good hygiene, the lens filter of the thermometer was replaced after use with each participant, and participants were given a sanitized plastic sleeve to place on their arm before using a blood pressure cuff. The pre-shift physiological parameter measurements were taken at the participants' housing camp before they went to the sugarcane field to avoid disturbing their work. The post-shift measurement was conducted at the sugarcane field after the end of the work shift. Before taking the measurements, the participants had rested for at least 10 min. Pictures from the pre-shift and post-shift physiological parameter measurements are shown in Figure 1. According to the American College of Cardiology and American Heart Association, blood pressure in an adult is classified into four categories: normal (SBP 90–119 mmHg and DBP < 80 mmHg), elevated (SBP 120–129 mmHg and DBP < 80 mmHg), hypertension stage 1 (SBP 130–139 mmHg or DBP 80–90 mmHg), and hypertension stage 2 (SBP ≥ 140 mmHg or DBP ≥ 90 mmHg) [14,15]. In our study, a low blood pressure category (SBP ≤ 89 mmHg or DBP ≤ 59 mmHg) [16] was also included, resulting in a total of five categories.

Figure 1. Sites of the two physiological parameter measurements: (**a**) pre-shift at the participants' housing camp and (**b**) post-shift at the sugarcane field.

The outcomes of interest in this study were post-shift physiological parameters including heart rate, systolic and diastolic blood pressures, and body temperature, considered as continuous variables. The pre-shift physiological parameters were included as covariates. The primary explanatory variable was $WBGT_{eff}$-FS-TWA, considered as a continuous variable. A directed acyclic graph (DAG), created using the DAGitty programme, version 3.1 [17], which illustrates our current understanding of the hypothesized causal relationships between the primary explanatory and outcome variables (Figure 2). The DAG represents our conceptual model of potential confounding and mediating variables, enabling appropriate adjustment to better estimate the true association

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between the exposure and the outcomes. This study included five groups of confounding variables, based on the DAG: (1) demographic variable group: gender, age, education, and work experience; (2) health metric variable group: BMI and medical conditions; (3) health behaviour variable group: alcohol drinking, smoking, caffeine intake, and last night's sleep duration; (4) mitigating variable group: total duration breaks and total fluid intake at work; and (5) working task group: main responsibility on the measurement day and harvesting method. There was one potential mediator in this study, which was hours worked on the day of measurement.

IBM SPSS Statistics for Windows, version 29.0.2.0 [18], was used to analyse the data. Descriptive statistics characterised the data in terms of frequency, percentage, mean, standard deviation (S.D.), and minimum and maximum values. The dependent t-test compared physiological parameter results between the pre-shift measurement and the post-shift measurement; this was tested based on normal as well as log-transformed data. General linear regression (GLM) investigated the effects of heat stress exposure, measured as $WBGT_{eff}$-FS-TWA, on the post-shift physiological parameter results. This study reported the results from models including pre-shift results and adjusted models that accounted for both pre-shift results and identified confounders. Furthermore, adjusted models with the potential mediator were investigated.

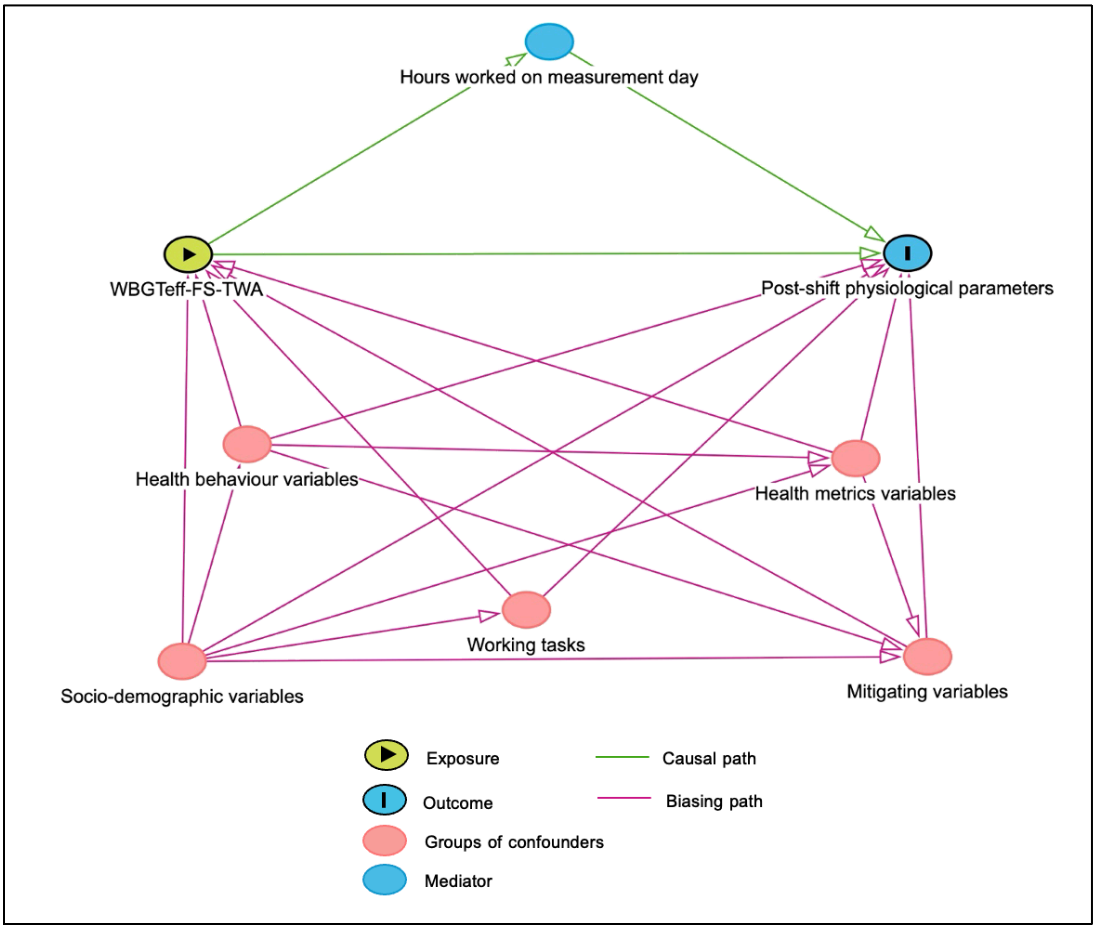

Figure 2. A Directed acyclic graph (DAG) showing the hypothetical causal relationships between the primary explanatory variable (a full work shift time-weighted average effective WBGT or $WBGT_{eff}$-FS-TWA) and the outcome variable (post-shift physiological parameters) along with groups of confounders (demographic variables, health metric variables, health behaviour variables, mitigating variables, working tasks) and the mediator (hours worked on the day of measurement).

3. Results

3.1. Demographic and Occupational Conditions of Participants

Of the 300 participants initially recruited, five were excluded from the analysis due to incomplete questionnaires, leaving a final sample of 295 participants, with 148 participating in the cooler months and 147 in the hotter month. The majority were male (55.9%) and their average age was 41 years (Table 1). All participants were paid by the piece or bundle. The mean measured WBGT was 28.6 ± 2.7 °C (27.3 ± 2.6 °C in cooler months vs. 30.4 ± 1.7 °C in hotter months). After adding CAF to the measured WBGT, the mean $WBGT_{eff}$-FS-TWA from both seasons was 31.3 ± 2.8 °C (Table 2).

Table 1. General characteristics of the study participants.

Descriptor	Category	Total (n = 295)	Cooler mo. (n = 148)	Hotter mo. (n = 147)
Socio-demographic variables				
Gender, n (%)	Male	165 (55.9)	77 (52.0)	88 (59.9)
	Female	130 (44.1)	71 (48.0)	59 (40.1)
Age (years), n (%)	Mean ± S.D.	41.3 ± 11.7	40.7 ± 11.1	42.0 ± 12.2
	Range	18.0–81.0	20.0–65.7	18.0–81.0
Educational level, n (%)	≤Primary school (6 years)	199 (67.5)	106 (71.6)	93 (63.3)
	Middle school (9 years)	65 (22.0)	28 (18.9)	37 (25.2)
	≥High school or technical school (12 years)	31 (10.5)	14 (9.5)	17 (11.6)
Work experience (years)	Mean ± S.D.	7.6 ± 7.4	8.4 ± 7.4	6.7 ± 7.3
	Range	4 d–36.0 y	4 d–36.0 y	2 m–31.0 y
Health metric variables				
BMI, n (%)	Underweight (<18.5 kg/m^2)	35 (11.9)	16 (10.8)	19 (12.9)
	Normal weight (18.5–22.9 kg/m^2)	141 (47.8)	69 (46.6)	72 (49.0)
	Overweight (23.0–24.9 kg/m^2)	39 (13.2)	15 (10.1)	24 (16.3)
	Obese I (≥25.0 kg/m^2)	80 (27.1)	48 (32.4)	32 (21.8)
Medical conditions, n (%)	No	241 (81.7)	120 (81.1)	121 (82.3)
	Yes	54 (18.3)	28 (18.9)	26 (17.7)
Health behaviour variables				
Current alcohol drinking, n (%)	No	143 (48.5)	65 (43.9)	78 (53.1)
	Yes	152 (51.5)	83 (56.1)	69 (46.9)
Current smoking, n (%)	No	154 (52.2)	79 (53.4)	75 (51.0)
	Yes	141 (47.8)	69 (46.6)	72 (49.0)
Caffeine intake, n (%)	No (no intake of coffee/tea/soft drink/energy drink)	12 (4.1)	5 (3.4)	7 (4.8)
	Yes (any intake of coffee/tea/soft drink/energy drink)	283 (95.9)	143 (96.6)	140 (95.2)
Last night sleep duration (hours)	Mean ± S.D.	8.3 ± 1.3	8.6 ± 1.3	8.0 ± 1.2
	Range	3.0–12.0	3.0–12.0	4.0–12.0
Mitigating variables				
Total duration of breaks per shift (hours)	Mean ± S.D.	1.3 ± 0.9	1.2 ± 0.9	1.4 ± 0.8
	Range	0.1–4.2	0.1–4.2	0.1–4.0
Total volume of liquids consumed at work (litres)	Mean ± S.D.	3.4 ± 1.8	2.8 ± 1.5	4.0 ± 1.9
	Range	0.5–10.3	0.5–8.6	0.5–10.3
Hours worked per day (hours)	Mean ± S.D.	10.1 ± 1.2	9.8 ± 1.3	10.4 ± 1.1
	Range	7.0–13.0	7.0–12.0	8.0–13.0
Days worked per week (days)	Mean ± S.D.	6.9 ± 0.6	6.8 ± 0.6	6.9 ± 0.5
	Range	1.0–7.0	1.0 –7.0	2.0–7.0
Hours worked per week (hours)	Mean ± S.D.	69.6 ± 10.4	67.4 ± 10.6	71.8 ± 9.8
	Range	10.0–91.0	10.0–84.0	20.0–91.0
Working task				
Primary responsibility on the measurement day, n (%)	Sugarcane harvesting only	281 (95.3)	137 (92.6)	144 (98.0)
	Sugarcane harvesting plus one additional high-physical-level task, i.e., levelling the loaded cane on the track using tools.	5 (1.6)	4 (2.7)	1 (0.7)
	Sugarcane harvesting plus one additional low-physical-level task, i.e., counting sugarcane, driving a tractor, or operating a sugarcane leaf remover	9 (3.1)	7 (4.7)	2 (1.4)
Harvesting methods on the measurement day	Mixed harvesting (unburnt and burnt) in one day	73 (24.7)	36 (24.3)	37 (25.2)
	Harvesting unburnt sugarcane	103 (34.9)	81 (54,7)	22 (15.0)
	Harvesting burnt sugarcane	119 (40.3)	31 (20.9)	88 (59.9)

Table 2. $WBGT_{eff}$-FS-TWA results of the study participants.

$WBGT_{eff}$-FS-TWA (°C)	n (%)		
	Total (n = 295)	Cooler Months (n = 148)	Hotter Months (n = 147)
>34.0	29 (9.8)	0 (0)	29 (19.7)
32.1–34.0	128 (43.4)	44 (29.7)	84 (57.1)
30.1–32.0	37 (12.5)	16 (10.8)	21 (14.3)
28.1–30.0	62 (21.0)	53 (35.8)	9 (6.1)
26.1–28.0	24 (8.1)	20 (13.5)	4 (2.7)
≤26.0	15 (5.1)	15 (10.1)	0 (0)
Mean ± S.D.	31.3 ± 2.8	29.8 ± 2.7	32.8 ± 2.0
Range	22.9–35.4	22.9–33.9	26.0–35.4

$WBGT_{eff}$-FS-TWA = full work shift time-weighted average effective wet bulb globe temperature.

3.2. Pre-Shift and Post-Shift Physiological Parameters

The average pre-shift measurement time of day was 05:47, with a range of 04:46–07:52, while the average post-shift measurement time was 16:38, with a range of 13:37–18:18. Table 3 shows pre-shift and post-shift results of participant physiological parameters including blood pressure, heart rate, and body temperature. The average pre-shift and post-shift rest period duration before taking the physiological parameter measurements were 16.3 ± 5.7 and 16.3 ± 7.4 min, respectively. According to the protocol of physiological parameter measurement, the participants had to rest for at least 10 min. However, there was one participant who had rested only 8 min before the pre-shift measurement. This participant was still included in the analysis because their rest period was within approximately 1.5 standard deviations of the cohort mean and their measurement was consistent with the rest of the group. Both types of blood pressure (systolic and diastolic) were significantly lower at post-shift (p-value < 0.001). The participants' heart rate and body temperature were higher at post-shift (p-value < 0.001). Similar results were obtained when using log-transformed results (Supplementary Material, Table S1). Table 4 shows blood pressure interpretation categories and the distribution of participant results within those categories, both pre-shift and post-shift. At both pre- and post-shift measurements, the largest percentage of participants were in the normal blood pressure group, at 37.3% and 48.8%, respectively.

Table 3. Pre-shift and post-shift results of participant physiological parameters—blood pressure, heart rate, and body temperature.

Parameter	**Season**	**Mean ± S.D. (Range)**			***p*-value** †
		Pre-Shift	**Post-Shift**	**Difference (Post-Pre)**	
Systolic blood pressure (mm Hg)	Total (n = 295)	123.1 ± 15.3 (82.0, 174.0)	118.9 ± 14.0 (81.0, 174.0)	−4.2 ± 11.5 (−46.0, 59.0)	<0.001
	Cooler mo. (n = 148)	126.4 ± 16.3 (82.0, 174.0)	121.6 ± 14.3 (89.0, 174.0)	−4.8 ± 12.3 (−37.0, 59.0)	<0.001
	Hotter mo. (n = 147)	119.7 ± 13.5 (88.0, 166.0)	116.1 ± 13.1 (81.0, 157.0)	−3.6 ± 10.7 (−46.0, 32.0)	<0.001
Diastolic blood pressure (mm Hg)	Total (n = 295)	78.1 ± 10.0 (48.0, 112.0)	75.5 ± 9.6 (46.0, 113.0)	−2.6 ± 6.5 (−24.0, 28.0)	<0.001
	Cooler mo. (n = 148)	80.1 ± 10.5 (53.0, 112.0)	77.1 ± 10.1 (46.0, 113.0)	−3.1 ± 6.8 (−23.0, 28.0)	<0.001
	Hotter mo. (n = 147)	76.0 ± 9.0 (48.0, 104.0)	73.8 ± 8.9 (53.0, 101.0)	−2.2 ± 6.2 (−24.0, 13.0)	<0.001
Heart rate (bpm)	Total (n = 295)	69.3 ± 11.0 (43.0, 106.0)	84.1 ± 11.2 (51.0, 121.0)	14.8 ± 9.3 (−13.0, 47.0)	<0.001
	Cooler mo. (n = 148)	69.4 ± 11.6 (43.0, 106.0)	83.0 ± 11.8 (51.0, 117.0)	13.6 ± 8.6 (−6.3, 44.7)	<0.001
	Hotter mo. (n = 147)	69.3 ± 10.4 (49.0, 99.0)	85.2 ± 10.4 (60.0, 121.0)	15.9 ± 9.9 (−13.0, 47.3)	<0.001
Body temperature [a] (°C)	Total (n = 295)	36.2 ± 0.5 (34.5, 37.2)	37.1 ± 0.3 (36.2, 38.4)	0.9 ± 0.5 (−0.5, 2.7)	<0.001
	Cooler mo. (n = 148)	36.1 ± 0.5 (34.5, 37.2)	37.0 ± 0.3 (36.2, 38.2)	0.9 ± 0.5 (−0.5, 2.7)	<0.001
	Hotter mo. (n = 147)	36.2 ± 0.4 (35.1, 37.2)	37.1 ± 0.3 (36.2, 38.4)	0.8 ± 0.5 (−0.3, 2.2)	<0.001

[a] Calculated from both left and right tympanic temperature readings; † Dependent t-test.

Table 4. Classification of blood pressure and distribution of participant readings pre-shift and post-shift.

Blood Pressure Interpretation	**SBP mmHg**		**DBP mmHg**	**Total (n = 295)**		**Cooler mo. (n = 148)**		**Hotter mo. (n = 147)**	
				Pre n (%)	**Post n (%)**	**Pre n (%)**	**Post n (%)**	**Pre n (%)**	**Post n (%)**
Low	≤89	or	≤59	4 (1.4)	12 (4.1)	1 (0.7)	2 (1.4)	3 (2.0)	10 (6.8)
Normal	90–119	and	<80	110 (37.3)	144 (48.8)	39 (26.4)	63 (42.6)	71 (48.3)	81 (55.1)
Elevated	120–129	and	<80	41 (13.9)	38 (12.9)	20 (13.5)	20 (13.5)	21 (14.3)	18 (12.2
Hypertension stage 1	130–139	or	80–90	87 (29.5)	69 (23.4)	55 (37.2)	44 (29.7)	32 (21.8)	25 (17.0)
Hypertension stage 2	≥140	or	≥90	53 (18.0)	32 (10.8)	33 (22.3)	19 (12.8)	20 (13.6)	13 (8.8)

Adapted from American College of Cardiology and American Heart Association [14–16]; SBP = Systolic blood pressure; DBP = Diastolic blood pressure.

3.3. Effects of Heat Stress Exposure on Physiological Parameters

Table 5 shows the associations, based on the results of the GLMs, between heat stress exposure ($WBGT_{eff}$-FS-TWA) and post-shift physiological parameters. Based on the adjusted model, no significant association was found between $WBGT_{eff}$-FS-TWA and both post-shift systolic blood pressure and post-shift diastolic blood pressure. However, for every degree Celsius increase in $WBGT_{eff}$-FS-TWA, post-shift heart rate increased by 0.61 beats per minute (bpm), and post-shift body temperature increased by 0.02 °C, after adjusting for pre-shift values and other relevant confounding variables. The full model details that adjusted for pre-shift results and other available confounding variables are provided in Supplementary Material, Table S2 for blood pressure and Table S3 for heart rate and body temperature. No evidence of a mediating effect by "hours worked on measurement day" was observed (Supplementary Material, Table S4).

Table 5. Associations between heat stress exposure and post-shift physiological parameters (n = 295).

Outcome	Explanatory variable: $WBGT_{eff}$-FS-TWA (per 1 °C Increase)	
	Model adjusted for pre-shift results	Adjusted model [a]
	β (95%CI)	β (95%CI)
Post-shift systolic blood pressure (mmHg)	−0.46 (−0.88, −0.05)	−0.33 (−0.76, 0.11)
Post-shift diastolic blood pressure (mmHg)	−0.21 (−0.46, 0.04)	−0.21 (−0.48, 0.05)
Post-shift heart rate (bpm)	0.58 (0.24, 0.92)	0.61 (0.24, 0.98)
Post-shift body temperature (°C)	0.01 (0.001, 0.03)	0.02 (0.002, 0.03)

$WBGT_{eff}$-FS-TWA = full work shift time-weighted average effective WBGT; bpm = beats per minute. [a] adjusted for pre-shift result; demographic variable group: gender, age, education, and work experience; health metrics variable group: BMI and medical conditions; health behaviour variable group: alcohol drinking, smoking, caffeine intake, and last night's sleep duration; mitigating variable group: total duration breaks and total fluid intake at work; working task group: main responsibility on the measurement day and harvesting method.

4. Discussion

The study investigated the effect of $WBGT_{eff}$-FS-TWA on blood pressure, heart rate, and body temperature among Thai sugarcane workers. The results indicate that their systolic and diastolic blood pressures had significantly decreased at post-shift, while their heart rate and body temperatures had significantly increased at post-shift. No significant association was found between $WBGT_{eff}$-FS-TWA and both post-shift systolic and diastolic blood pressure. However, post-shift heart rate and body temperature values increased with increasing heat stress exposure.

The significant decrease in both systolic and diastolic blood pressures after the shift is expected. It is common for both types of blood pressures to decrease for several hours after strenuous exercise [19]. This occurs due to a reduction in cardiac output or systemic vascular resistance, both of which are influenced by changes in cardiac autonomic modulation and vasomotor sympathetic activity induced by prior exercise [20]. In healthy individuals, this reduction typically lasts up to 2 h, while in hypertensive patients, it may persist for more than 12 h. Exercising in hot conditions can further exacerbate this effect because blood vessels dilate to promote cooling [21,22]. These findings (i.e., the post-shift reduction in systolic and diastolic blood pressures) differ from those reported by Boonruksa, Maturachon, Kongtip and Woskie [4] who found that systolic and diastolic blood pressures among Thai sugarcane harvesters had significantly increased at post-shift measurement, compared to pre-shift measurement. The difference might be because of the timing of pre-shift measurements. This study measured physiological parameters in the early morning, close to 6:00 and again after finishing work, shortly before 17:00. Morning blood pressure normally surges during the first 2 h after awakening. Our data were collected very early in the morning (around 6 am) at the workers' camps, likely capturing the natural surge in blood pressure during the first 2 h after awakening [23,24], while Boomruksa et al. measured blood pressure when the workers were already at sugarcane field, which is likely to be later in the morning.

The participants in the current study had significant increased heart rates after the shift (at the average of 84 bpm) compared to pre-shift (average 69 bpm). This aligns with Boonruksa's study [4] which also found a significant rise in heart rate at the post-shift measurement. The pre- and post -shift heart rates of the current study were still within the normal resting heart rate range for most healthy adults of 50–90 bpm which fluctuates throughout the day, decreasing at night [25]. To accommodate the body's changing need for oxygen, heart rate generally speeds up and slows down depending on activities throughout the day, and it varies among individuals. Importantly, a resting heart rate that is higher than normal or a maximum heart rate that is lower than normal can increase the risk of heart disease or other medical conditions [26]. In healthy individuals, resting for 5–10 min is generally sufficient for heart rate to return to resting level after exercise [27,28]. The post-exercise increase in heart rate may indicate a real effect. However, it should be noted that heart rate may also be higher in the afternoon due to circadian rhythms [29]. It is also important to note that this 5–10-min recovery period applies to exercise performed under normal environmental condition; when exercising in hot conditions, it takes longer for heart rate to return to baseline values after exercise. This effect is particularly pronounced in higher relative humidity conditions, where heart rate variation and overall cardiovascular strain may take between 8 and 24 h to return baseline, compared to about 4 h in drier environments [30]. Heat stress has been observed to delay immediate post-exercise heart rate recovery because blood volume is reduced and the heart keeps working to support cooling [31]. Therefore, it is possible that after the sugarcane workers strained in the heat, resting for 10 min before taking the post-shift heart rate measurement may not have been sufficient to allow for accurate comparison with the pre-shift resting levels. For practical reasons, the current study faced time constraints in measuring large numbers of workers. In further study, a longer waiting period would allow for greater accuracy of the measurements. However, the influence of circadian rhythms should also be considered.

The study participants' body temperatures significantly increased from 36.2 ± 0.5 °C, at pre-shift to 37.1 ± 0.3 °C, at post-shift. Boonruksa, Maturachon, Kongtip and Woskie [4] found similar results. However, it is important to note that the minimum body temperature in healthy people occurs in the early morning about 2 h before wakening (i.e., 5:00–7:00) [32], and that time corresponds to the pre-shift measurement period in the current study. Among typical adults in the general population, mean daily temperature can vary by about 0.5 °C, with daily variations ranging from 0.25 to 0.5 °C [33]. Additionally, the daily variation in body temperature has been found to be significantly greater in younger healthy individuals (average amplitude of 0.28 °C), compared to older healthy adults (average amplitude of 0.2 °C) [Czeisler et al., 1992, as cited in 32]. This study used tympanic temperature to represent body temperature. According to ISO 9886 (Ergonomics—evaluation of thermal strain by physiological measurements), body temperature can be approximated by the measurement of temperature at different points of the body, and one of the recommended measurements is tympanic temperature [34]. Mah et al. [35] compared body temperature measurements at different sites (i.e., oral, forehead, ear, and face) using different devices found that not all methods of temperature monitoring are equally effective and that the most accurate commercially available method for the regular measurement of body temperature is a tympanic thermometer.

There were no statistically significant associations between $WBGT_{eff}$-FS-TWA and post-shift diastolic or systolic blood pressures, after adjusting for pre-shift results and other available confounding variables. However, the relationships show negative trends. Barnett et al. [36], who used data on systolic blood pressure from a total of 115,434 participants aged 35–64 years in 16 countries, found that each 1-degree Celsius increase in outdoor temperature reduced blood pressure by an average of 0.19 mmHg (95% posterior interval: −0.26, −0.11). Blood pressure in young and middle-aged adults decreases in high ambient temperatures, potentially leading to orthostatic hypotension or postural hypotension with an increase in dizziness, fainting and falls in older adults [37]. The reason for lower blood pressure during exposure to heat is that blood vessels dilate in order to regulate core body temperature. The combination of reduced blood pressure caused by the dilation of blood vessels from heat and dehydration from sweating can cause heat-related symptoms i.e., dizziness and fainting [38]. It is important to note that long-term variability in blood pressure is associated with cardiovascular and mortality consequences [39]. A review study by Liu et al. [40] reported that with every degree Celsius increase in ambient temperature, there was a positive association with cardiovascular disease-related mortality for all diagnoses considered. There is also suggestion of a negative association between ambient temperature and diastolic blood pressure among elderly men [41]. Based on our review of the literature, there are no published studies specifically determining the relationship between WBGT and blood pressure in agricultural workers. This gap highlights the need for more research exploring how occupational heat stress exposure, as quantified by WBGT, affects cardiovascular responses in agricultural settings. On the other hand, research in other occupational settings, such as miners in Tanzania conducted by Meshi et al. [42] and in Iran studied by Teymori et al. [43], have investigated this association more directly, and found that the average WBGT showed a positive correlation with a rise in systolic blood pressure, which is in contrast with results from the current study. This discrepancy may be explained by the different timing of pre-shift measurement and the use of bivariate analysis in their study, which did not adjust for potential confounders and may therefore limit the validity of the observed associations.

The current study also found that raised $WBGT_{eff}$-FS-TWA was associated with a significant increase in post-shift heart rate, adjusted for pre-shift heart rate and other available confounding variables ($\beta = 0.61$, 95% CI 0.24, 0.98). This is a small effect size, equivalent to less than 1 bpm increase per unit of heat stress exposure, which is unlikely to be of substantial clinical importance. High ambient temperature exposure causes a significant increase in heart rate among healthy male participants, reported by Bruce-Low et al. [44]. However, the significant increase found in Bruce-Low et al.'s study was between pre-exposure (average heart rate of 66.5 bpm) and during exposure to dry heat in a sauna (106.0 bpm). A rise in heart rate is linearly associated with an increased ambient temperature, increasing by as much as 40% as body temperature rises Gorman & Proppe, 1984 as cited in [45]. This is a typical cardiovascular response to heat stress exposure, which includes increased skin blood flow, cardiac output, and heart rate [46]. However, Meshi, Kishinhi, Mamuya and Rusibamayila [42] reported contrasting correlations involving heart rate. They observed a very weak negative correlation between the average WBGT and the rise in heart rate (R = −0.05, *p*-value = 0.701), but a very weak positive correlation between the average dry-bulb temperature (Tdb) and the rise in heart rate (R = 0.01, *p*-value = 0.962).

The current study found that the $WBGT_{eff}$-FS-TWA was significantly correlated with an increase in post-shift body temperature results, adjusting for pre-shift results and other available confounding variables. Meshi, Kishinhi, Mamuya and Rusibamayila [42] found a significant association between the average WBGT and the rise in core body temperature among miners in Tanzania ($r^2 = 0.168$). For each 1 °C increase in the average WBGT, there was an associated average change of 0.17 °C in core body temperature. However, that was a bivariate analysis. Our multivariate model, which adjusted for the participants' primary work responsibilities and other confounders, reinforces that while heat exposure ($WBGT_{eff}$-FS-TWA) is a significant factor, the physical intensity of manual harvesting remains a critical contributor to heat strain. This aligns with the understanding that internal metabolic heat production from strenuous labour can play a role as significant as ambient conditions in this occupational setting. A key finding of this study is the relative stability of body temperature despite increasing environmental heat; specifically, body temperature increased by only 0.02 °C for every 1 °C rise in WBGT. This suggests that while environmental heat is a significant predictor, its absolute impact on core temperature in this cohort is minimal. The relative stability of body temperature despite rising WBGT suggests that workers engaged in self-pacing. This behavioural regulation, involving a reduction in work intensity during periods of high thermal stress, is a primary mechanism for maintaining a stable core temperature. Consequently, the low coefficient observed in our model likely reflects the workers' ability to modulate exertion levels to prevent overheating. Notably, participants were compensated via a piece-rate system, which typically incentivizes workers to override physiological signals to maximize productivity. However, the marginal rise in core temperature suggests that self-pacing still occurred, indicating that at high levels of combined metabolic and environmental heat, behavioural regulation becomes a necessary safety threshold despite financial incentives. The relative stability of body temperature may also be attributed to heat acclimatization. Although not formally assessed, the participants were experienced harvesters with prolonged seasonal exposure. Such long-term exposure is known to enhance thermoregulatory efficiency, likely contributing to the stable core temperatures observed despite rising environmental heat.

The outcomes of the current study highlight the physiological parameters imposed by heat exposure, as shown in the significant correlations between heat stress exposure and increased heart rate and elevated body temperature. Although there was no significant relationship between heat stress exposure and either type of blood pressure, both parameters tended to decrease with increased rising heat stress exposure. This suggests a possible heat-induced physiological response that warrants further investigation. This study contributes to the understanding of how heat stress exposure affects cardiovascular outcomes and highlights the need for practical measures to reduce heat stress exposure and thereby reduce physiological parameter responses. It would be helpful to monitor physiological parameters during rest breaks. For example, if a worker's body temperature remains elevated (≥37.5 °C), they should not return to work and should continue hydrating and cooling. Currently, formal occupational health and safety regulations in Thailand do not apply to informal workers. The Thai government and other relevant organisations should create policies and regulations that also protect informal workers' health and wellbeing. The environmental parameters contributing to the WBGT, including dry-bulb, natural wet-bulb, and globe temperatures, were reported in detail previously [6]. Briefly, while all parameters were significantly higher during the hotter month, globe temperatures (42.6 ± 3.1 °C) were notably high. This observation underscores the need for radiant heat protection, such as shaded rest areas and broad-brimmed hats, especially as current practices show a lack of standardised headwear.

The current study has several notable strengths. Blood pressure, heart rate, and body temperature data were collected using objective methods, contributing to the reliability of the study results. The WBGT and physiological measurements were conducted during both the cooler and hotter months of the harvesting season, ensuring that the data included the potentially hottest conditions. Another strength of the study is that it recorded participants' clothing and accounted for the CAF to adjust the WBGT results accordingly. However, some limitations need to be considered. The nature of cross-sectional design does not lend itself to causal effect analysis. The physiological measurements were not collected during the work shift itself because of budget and time constraints, but continuous measurements throughout the work shift would be useful. These could provide information on how physiological parameters vary during work, particularly during the hottest times of the day, and during rest periods. This study also did not investigate other potential confounding variables, for example acclimatisation to heat or physical activity levels. Although the main responsibility was included as a covariate in the analysis, metabolic rates naturally vary among individuals. Thus, assessment of individual workload through observation level (time and motion study method) or analysis level (heart rate measurement while working) or expertise level (oxygen consumption measurement), according to ISO 8996:2021 Ergonomics of the thermal environment—Determination of metabolic rate [47] could provide additional insight. Ambient temperature was not recorded during the pre-shift period. While baseline physiological data were established, the specific environmental conditions at that time were not documented, potentially limiting the characterization of the initial thermal environment. While this study recorded the volume of fluid intake reported by participants, dehydration and sweat loss were not precisely quantified via pre- and post-shift weighing or urine output monitoring; therefore, a detailed water balance could not be established. Incorporating these gravimetric measures in future studies would allow for a more granular assessment of the relationship between hydration status and thermal strain, providing a more comprehensive evaluation of physiological strain in this population.

5. Conclusions

There is some evidence that high temperatures may increase physiological parameter responses, as indicated by correlations between heat stress exposure and elevated heart rate and body temperature among Thai sugarcane workers. These appear to be minor changes that may depend on temperature, and it remains unclear to what extent they are clinically important, even though the findings are statistically significant. These findings underline the importance of monitoring the body's cardiovascular and thermoregulatory responses to heat, especially as the world's temperatures increase and heat stress becomes a particular concern. Further studies should investigate the variabilities of physiological responses throughout the work shift and test the responses to interventions aimed at reducing heat stress exposure. Effective heat control strategies such as readily accessible hydration, an acclimatisation programme, and a work-rest-shade policy should be implemented. By examining the physiological impacts of heat stress exposure, this study contributes valuable data needed to address heat-related health issues among agricultural populations in tropical climates.

Supplementary Materials

The additional data and information can be downloaded at: https://media.sciltp.com/articles/others/2603231037272074/WAH-25110156-SM.pdf. Table S1: Log-transformed pre-shift and post-shift results of participant physiological parameters - blood pressure, heart rate, and body temperature (n = 295). Table S2: The full model details that adjusted for pre-shift results and other available confounding variables: β (95% CI) of blood pressure. Table S3: The full model details that adjusted for pre-shift results and other available confounding variables: β (95% CI) of heart rate and body temperature. Table S4: Summary results from additional models exploring the effect of specific groups of confounders (Models 1–5) and a mediator (Model 6) in a step-by-step process: β (95% CI) of post-shift physiological parameters.

Author Contributions

T.T.: writing—original draft; T.T., A.P.; H.A.S., M.G. and M.v.T.: conceptualization, data curation, formal analysis, investigation, methodology, project administration, resources, software; supervision, validation, visualization, and writing—review & editing. All authors have read and agreed to the published version of the manuscript.

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Institutional Review Board Statement

The study was conducted according to the guidelines of the Declaration of Helsinki and approved by the University Research Ethics Committee (UREC) of The University of Manchester (Ref No. 2022-15332-26084), and also by the Institutional Review Board of Naresuan University, Thailand (IRB No. P2-0368/2565).

Informed Consent Statement

All participants were thoroughly informed about the study's nature beforehand and provided signed consent to participate.

Data Availability Statement

The datasets generated during and/or analysed during the current study are not publicly available but are available from the corresponding author on reasonable request.

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Conflicts of Interest

The authors declare no competing interests.

Use of AI and AI-Assisted Technologies

No AI tools were utilized for this paper.

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