

Effect of occupation-related heat stress exposure on productivity among sugarcane workers in Thailand

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Objectives Climate change affects a wide range of issues, including work productivity due to elevated temperatures. This is particularly important for agricultural workers in tropical countries like Thailand. This cross-sectional study aims to investigate the effects of heat stress exposure on productivity among Thai sugarcane workers during harvesting seasons.

Methods This study involved 287 sugarcane workers from Nakhon Sawan Province, Thailand, during the cooler or hotter 2023 harvesting periods. Information was collected on their demographic characteristics, health behaviors, working conditions, and work output (sugarcane stalks harvested). Wet bulb globe temperature (WBGT) was recorded in the fields during 14 cool and 11 hot season days. A full work shift time-weighted average effective WBGT (WBGT_{eff}-FS-TWA), adjusted for clothing factors, was calculated to provide an estimate of heat stress exposure over a full work shift. Multiple linear regression determined the effects of heat stress exposure on the average number of sugarcane stalks harvested per hour adjusting for available confounders.

Results Recorded WBGT_{eff}-FS-TWA values averaged 31.3°C [standard deviation (SD) 2.8, range 22.9–35.4°C]. The mean number of stalks harvested per hour was 387, SD 185, with higher rates observed when harvesting burnt sugarcane and working solo. For every 1°C rise in WBGT_{eff}-FS-TWA above the lowest observed baseline of 22.9°C, the average number of sugarcane stalks harvested decreased by 9 stalks per hour (β -8.59, 95% confidence interval -16.19– -0.99).

Conclusion Increased heat stress exposure decreases overall productivity. As global temperatures rise, heat stress increases, significantly impacting agricultural output alongside worker health.

Key terms agricultural worker; climate change; harvesting period; productivity loss; wet bulb globe temperature.

Increasing global temperatures caused by climate change have become a major concern. Thailand is located in the tropics, so the country is generally hot and humid. The average annual temperature in Thailand has increased by a total of 0.7°C, over the last century (1, 2). In Thailand, the average annual temperature in 2024 was 28.5°C, the highest recorded in the past 73 years (1951–2024) (3). This aligns with global temperatures, as 2024 was recorded as the warmest year since the recording of global temperatures began in 1850 (4).

Sugarcane is Thailand's top economic crop (5). Each year over the past decade, it has been cultivated on more than 16 billion square meters of land across 47 provinces. In 2023, Nakhon Sawan Province had the largest sugarcane cultivation area of any Thai province, at 1.3 billion square meters, with approximately 6.4 million tons of harvested sugarcane sent to sugar mills (6). Thai sugarcane harvesters perform heavy work that exposes them to extreme heat for long hours in the fields. Our earlier work showed that Thai sugarcane

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workers experience high heat exposure (7) and report a high prevalence of heat related-symptoms (8, 9). Thai sugarcane workers' heat stress has been found to exceed the recommended exposure limits established by Thailand as well as those of the American Conference of Governmental Industrial Hygienists (ACGIH) (7, 10–12). Compounding the situation, these workers are an informal workforce that is not employed under formal or legally recognized arrangements, and therefore the Thai regulatory standards for occupational health and safety are not officially enforceable in their case (11).

Increasing global temperatures pose a growing risk of negative health effects for agricultural workers, who are recognized as a high-risk occupational group (13), especially Thai sugarcane harvesters (10, 11). Although some studies have investigated the relationship between heat exposure and a decrease in labor productivity (14–17), there are a limited number of studies on how increasing heat stress exposure affects productivity. This gap is particularly important in Thailand's agricultural sector, where workers are highly vulnerable to rising global temperatures. The purpose of this study was to investigate the relationship between heat stress exposure and productivity in terms of the average number of sugarcane stalks harvested by Thai sugarcane workers.

Methods

General study design

Details regarding the study design, setting, study period, participant selection, heat stress assessment, and questionnaire have been reported previously (7). This cross-sectional study was conducted in sugarcane workers in the Khao Kala Sub-district, Phayuha Khiri District of Nakhon Sawan Province in Thailand. Workers from 13 camps (temporary living sites during the harvesting period) participated in the study. During Thailand's 2023 sugarcane harvest, 25 days of data were collected: 14 non-consecutive cooler-season days (mid-January to mid-February) and 11 consecutive hot-season days (March). Participants were sampled once, with no overlap between days. University of Manchester (UREC 2022-15332-26084), and Naresuan University, Thailand (IRB P2-0368/2565) approved the study. All participants provided written informed consent.

Questionnaire

Five trained field representatives supervised by the research team interviewed participants regarding demographic characteristics, health behaviors, working conditions, and 21 heat-related symptoms from the preceding week.

Heat stress assessment

The wet bulb globe temperature (WBGT) index, representing occupational heat exposure, was assessed following ISO 7243:2017 standards (18). WBGT instruments (TSI Quest, Model: QUESTemp 34; calibrated 9 January 2023) were placed in the fields for a full work shift (06:00–17:00 hours). Daily calibration was performed before and after data collection using a verification module attached to the sensor. Measurements were recorded every 5 minutes, including natural wet-bulb temperature (T_{nwb}), dry-bulb temperature (T_{db}), globe temperature (T_g), relative humidity (Rh), and WBGT. For outdoor conditions, WBGT was calculated as $0.7T_{nwb} + 0.2T_g + 0.1T_a$. To account for clothing, a clothing adjustment factor (CAF) was added: 0°C for standard cotton clothing and 3°C for double-layer woven clothing (19). For three-layer clothing, the same 3°C CAF was applied due to lack of specific guidance. Clothing data were obtained through observation and a 7-day recall questionnaire. The full-shift time-weighted average effective WBGT (WBGT_{eff}-FS-TWA) was calculated individually by averaging WBGT over the work shift and adding the CAF.

Productivity assessment

Information on participants' productivity was collected by counting the number of sugarcane stalks harvested by each worker per day. Generally, the stalks were grouped into bundles, which were then grouped into piles. The number of stalks in each bundle and pile varied, depending on the farmer's instructions. Three different arrangements were used in various fields: 1 pile=3 bundles, with 1 bundle=20 stalks; 1 pile=5 bundles, with 1 bundle=20 stalks; and 1 pile=50 stalks (without bundles). However, among the workers, the common practice is for 1 pile to consist of 5 bundles, with each bundle containing 20 stalks. The researchers counted the piles of stalks each worker made at different times of the day: at approximately 09:00, 12:00, and 15:00 hours and the end of work. These counts were verified by the workers, who also kept their own records. The study then calculated the total number of stalks harvested over the course of the day, no matter how they were arranged into bundles and piles. Of 287 participants, 9 harvested sugarcane along with one other task. In this case, only the number of harvesting hours was used. The total number of stalks per worker was then divided by the number of harvesting hours worked to get the average number of stalks per hour worked.

Variables of interest

The outcome of interest was the average number of

stalks harvested per hour, considered as a continuous variable. The primary explanatory variable was WBGT_{eff}-FS-TWA, treated as a continuous variable. A directed acyclic graph (DAG) was developed using DAGitty (version 3.1) (20), which outlines our best understanding of (i) the hypothetical causal relationships between our primary explanatory variable and outcome variable and (ii) potential confounding and mediating variables present, allowing for appropriate adjustment where possible when targeting a true association due to primary exposure (supplementary material, www.sjweh.fi/article/4336, figure S1).

Six groups of confounders were defined based on the DAG. First, the socio-demographic variables were gender, age, education, and work experience. Second, the health metrics included body mass index (BMI) and medical conditions. Third, health behavior included alcohol consumption, smoking, caffeine intake, and last night's sleep duration. Fourth, mitigating variables were total duration of breaks and total fluid intake at work. Fifth, the work-related variables included harvesting approach and harvesting method. Harvesting approach was categorized as harvesting with three workers, two workers, or solo. Harvesting methods included burnt sugarcane, unburnt sugarcane, or a combination. Unburnt harvesting was further divided into two types: with manual leaf removal, and without leaf removal (where leaves were mostly removed by machine). Based on actual work patterns, participants were classified into five groups (i): burnt sugarcane (ii), unburnt with leaf removal (iii), unburnt without leaf removal (iv), approximately 25% burnt and 75% unburnt without leaf removal, and (v) approximately 75% burnt and 25% unburnt with leaf removal. These proportions reflect observed data groupings. Finally, heat-related symptoms in the previous seven days were included as a confounder, categorized into <50th, 50th–75th, and >75th percentile. One mediator was identified: hours worked on the day of data collection.

Data analysis

Data was analyzed using SPSS Statistics for Windows, version 29.0.2.0, (IBM, Armonk, NY, USA). Descriptive statistics characterized the data in terms of frequency, percentage, mean, standard deviation (SD), and range. Linear regression explored the effects of heat stress exposure (WBGT_{eff}-FS-TWA) on the average number of stalks harvested per hour. Both unadjusted and adjusted models (including all identified confounders) were reported, with model details provided in supplementary table S1. Additional analyses included an adjusted model incorporating the potential mediator and step-wise models assessing groups of confounders; results are shown in supplementary table S2. Scatter plots of

WBGT_{eff}-FS-TWA and harvesting productivity were generated, with markers indicating gender. Sensitivity analysis was conducted to assess the influence of outliers by removing observations with high leverage, identified using Cook's distance and leverage values.

Results

Of the 300 sugarcane workers recruited, 13 were excluded due to incomplete questionnaires, leaving 287 participants. Males slightly outnumbered females (56.1% versus 43.9%). The mean age was 41 years, with an average of 7.5 years of work experience (table 1). The overall mean WBGT_{eff}-FS-TWA was 31.3 (SD 2.8, range 22.9–35.4)°C. Exposure was higher in hotter months (32.8, SD 2.0, range 26.0–35.4°C) than in cooler months (29.8, SD 2.7, range 22.9–33.9°C). Participants harvested an average of 387 stalks per hour. Higher productivity was observed during hotter months, when harvesting burnt sugarcane, and during solo work (table 2). The scatter plot (figure 1) shows a negative relationship between WBGT_{eff}-FS-TWA and harvesting rate, both overall and stratified by gender.

Effects of heat stress exposure on the average number of sugarcane stalks harvested per hour

Table 3 describes the associations observed with the regression model between WBGT_{eff}-FS-TWA and the average number of stalks harvested per hour. Both the unadjusted and adjusted models reported a negative effect, with the unadjusted β -9.57 [95% confidence interval (CI) -17.14– -2.01] and the adjusted β -8.59 (-16.19– -0.99) per 1°C increase in WBGT_{eff}-FS-TWA above the lowest observed baseline of 22.9°C. Full model details are provided in supplementary table S3. There were three potential leverage points that may have strongly influenced the regression analysis, as shown in supplementary figure S2. After removing the leverage points collectively, the results indicate that the association was noticeably attenuated from β -8.59 (95% CI -16.19– -0.99) to β -3.23 (95% CI -10.83–4.37), based on the adjusted model supplementary table S4. An interaction between exposure and gender was not statistically significant, indicating no evidence of a difference in exposure effect. The estimated effect was -7.81 for males and approximately -9.84 for females (ie, a 2.03-unit greater decrease than males) (table 3 and supplementary table S5). No evidence was observed of the potential mediating effect of hours worked on the day of measurement on the exposure productivity association (supplementary table S2).

Table 1. Study participant profile separated by gender (N=287).

	Total (N=287)		Male (N=161)		Female (N=126)	
	N (%)	Mean (range)	N (%)	Mean (range)	N (%)	Mean (range)
Age (years)		41.4 (18.0–81.0)		41.1 (18.0–81.0)		41.9 (18.0–64.0)
Educational level						
≤Primary school (6 years)	194 (67.6)		107 (66.5)		87 (69.0)	
Middle school (9 years)	63 (22.0)		37 (23.0)		26 (20.6)	
≥High school or technical school (12 years)	30 (10.5)		17 (10.6)		13 (10.3)	
Work experience (years) ^a		7.5 (4.0–36.0) ^a		7.5 (4.0–31.0) ^a		7.6 (15.0–36.0) ^a
Body mass index		22.9 (14.3–39.6)		22.0 (15.6–36.4)		23.9 (14.3–39.6)
Medical conditions						
No	233 (81.2)		146 (90.7)		87 (69.0)	
Yes	54 (18.8)		15 (9.3)		39 (31.0)	
Alcohol consumption						
No	142 (49.5)		64 (39.8)		78 (61.9)	
Yes	145 (50.5)		97 (60.2)		48 (38.1)	
Smoking						
No	153 (53.3)		53 (32.9)		100 (79.4)	
Yes	134 (46.7)		108 (67.1)		26 (20.6)	
Caffeine intake						
No (no intake of coffee/tea/soft drink/energy drink)	12 (4.2)		8 (5.0)		4 (3.2)	
Yes (any intake of coffee/tea/soft drink/energy drink)	275 (95.8)		153 (95.0)		122 (96.8)	
Previous night's sleep duration (hours)		8.3 (3.0–12.0)		8.3 (3.0–12.0)		8.4 (5.0–12.0)
Total break duration per shift (hours)		1.3 (0.1–4.2)		1.3 (0.1–4.2)		1.3 (0.1–4.2)
Total volume of liquids at work (liters)		3.5 (0.5–10.3)		3.5 (0.5–10.3)		3.4 (0.5–8.6)
Harvesting methods						
25% burnt, 75% unburnt without leaf removal	6 (2.1)		4 (2.5)		2 (1.6)	
75% burnt, 25% unburnt with leaf removal	19 (6.6)		12 (7.5)		7 (5.6)	
Unburnt without leaf removal	87 (30.3)		46 (28.6)		41 (32.5)	
Unburnt with leaf removal	43 (15.0)		27 (16.8)		16 (12.7)	
Burnt	132 (46.0)		72 (44.7)		60 (47.6)	
Harvesting approach						
Group with 3 people	15 (5.2)		8 (5.0)		7 (5.6)	
Group with 2 people	101 (35.2)		53 (32.9)		48 (38.1)	
Solo	171 (59.6)		100 (62.1)		71 (56.3)	
Harvesting hours worked on the day of measurement (hours)		9.3 (5.0–11.0)		9.4 (5.0–11.0)		9.3 (7.3–10.9)

^a Duration in years with range of days (N) to years (N).**Table 2.** The average number of stalks harvested per hour per participant by season, harvesting method, harvesting approach, and wet bulb globe temperature (WBGT). [SD=standard deviation; WBGT_{eff}-FS-TWA=full work shift time-weighted average effective WBGT].

Category	N (%)	Stalks/harvesting hour	
		Mean (SD)	Range
Overall	287 (100)	387 (185)	94–1091
Seasons			
Cooler months	141 (49.1)	340 (158)	94–952
Hotter months	146 (50.9)	432 (197)	151–1091
Harvesting methods			
25% burnt, 75% unburnt without leaf removal	6 (2.1)	372 (91)	278–545
75% burnt, 25% unburnt with leaf removal	19 (6.6)	425 (175)	216–715
Unburnt without leaf removal	87 (30.3)	283 (98)	102–647
Unburnt with leaf removal	43 (15.0)	351 (125)	154–953
Burnt	132 (46.0)	462 (212)	94–1091
Harvesting approach			
Group with 3 people	15 (5.2)	237 (73)	102–421
Group with 2 people	101 (35.2)	325 (122)	128–775
Solo	171 (59.6)	437 (204)	94–1091
WBGT _{eff} -FS-TWA (°C)			
> 34.0	29 (10.1)	307 (108)	151–658
32.1–34.0	124 (43.2)	430 (203)	132–1091
30.1–32.0	37 (12.9)	358 (177)	101–854
28.1–30.0	59 (20.6)	385 (177)	94–857
26.1–28.0	23 (8.0)	342 (164)	184–953
≤26.0	15 (5.2)	333 (151)	182–715

Discussion

Thai sugarcane workers are informal workers exposed to heat for long hours in the fields. Heat stress is a key health concern, but its impact on productivity remains unclear. This study shows that increased heat stress reduces productivity, measured by the average number of stalks harvested per hour.

Although the effect of heat stress on productivity was modest (a decrease of 9 stalks/hour per 1°C increase in WBGT_{eff}-FS-TWA), it may have important implications for workers' income, as pay is often tied to output. Overall, a 1°C increase could result in a loss of about 24 022 stalks per day across 287 workers, assuming 9.3 working hours per day. This loss includes both burnt and unburnt sugarcane. While the exact payment the workers received from harvesting was not collected in this study, information gathered from informal discussions with farmers and workers suggests that payment rates typically range from 6 Thai Baht (THB) (approximately 0.17 USD) per pile for burnt sugarcane to 10–12 THB (0.29–0.34 USD) per pile for unburnt sugarcane

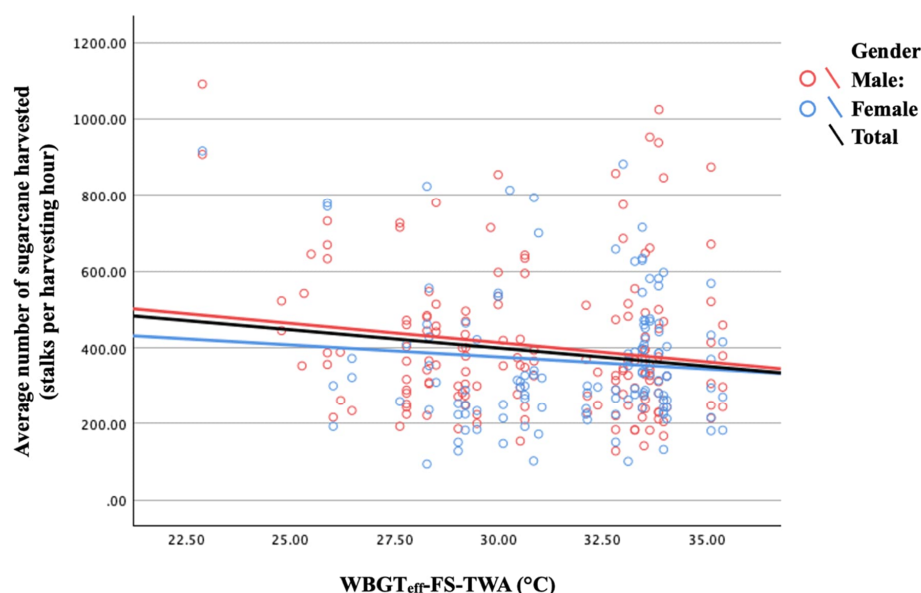


Figure 1. A scatter plot of full work shift time-weighted average effective wet bulb globe temperature ($WBGT_{eff}$ -FS-TWA) (X-axis) and the average number of stalks harvested per hour (Y-axis) by gender. Each point represents one participant with males shown as red circles and females as blue circles. Trend lines indicate the direction of association between the two variables, black for the overall sample, red for males, and blue for females.

(1 pile=5 bundles $\times$ 20 stalks). Based on the approximately 24 022 stalks per day among the 287 subjects in this study, this corresponds to about 240 piles lost per day, assuming 1 pile equals 100 stalks (5 bundles $\times$ 20 stalks). The estimated income loss ranges approximately from 1440 THB (~41 USD) (240 piles $\times$ 6 baht for burnt sugarcane) to 2880 THB (~82 USD) (240 piles $\times$ 12 baht for unburnt sugarcane) per day. Converting these figures highlights the tangible daily economic penalty imposed by heat stress on the agricultural workforce (exchange rate applied: 1 USD $\approx$ 35 THB). Heat exposure levels were high, particularly in hotter months, with 20% of workers experiencing $WBGT_{eff}$ -FS-TWA $>34^{\circ}\text{C}$, potentially exacerbating the issue.

Table 3. Full work shift time-weighted average effective wet bulb globe temperature ($WBGT_{eff}$ -FS-TWA) on the average number of stalks harvested per hour (stalks per harvesting hour). [CI=confidence interval]

Model	Explanatory variable	β (95% CI)
Unadjusted model	$WBGT_{eff}$ -FS-TWA	-9.57 (-17.14--2.01)
Adjusted model ^a	$WBGT_{eff}$ -FS-TWA	-8.59 (-16.19--0.99)
Adjusted model with the interaction term ^b	$WBGT_{eff}$ -FS-TWA	-7.81 (-17.15--1.52)
	Gender (female vs male)	40.38 (-404.36--485.12)
	$WBGT_{eff}$ -FS-TWA*Gender	-2.03 (-16.07--12.01)

^a Adjusted for demographic variable group: gender, age, education, and work experience; health metrics variable group: body mass index and medical conditions; health behavior variable group: alcohol consumption, smoking, caffeine intake, and last night's sleep duration; mitigating variable group: total duration breaks and total fluid intake at work; working task group: harvesting approach and harvesting method; and heat-related symptoms.

^b Adjusted model included the interaction term between $WBGT_{eff}$ -FS-TWA and gender; gender coded as 0=male, 1=female.

The robust negative association observed between heat stress and productivity is strongly anchored by our data from the coolest harvesting days. Specifically, conditions with minimal thermal burden ($WBGT_{eff}$ -FS-TWA $\leq 26^{\circ}\text{C}$) allowed workers to achieve productivity up to 715 stalks per hour. Although these extreme baseline observations exert high statistical leverage, they are valid and critical representations of the workers' maximum physiological capacity in the absence of heat stress. Excluding such points would artificially truncate the lower end of the environmental exposure spectrum, leaving only moderate-to-high heat conditions and significantly underestimating the true magnitude of heat-related productivity loss in agricultural settings.

Heat stress exposure may lead to productivity loss for several reasons. Being in severe heat stress exposure reduces work capacity and performance during working hours because the body requires more breaks to rehydrate and cool down (21, 22). Also, heat stress exposure and dehydration may cause more mistakes to be made, reducing labor productivity and increasing accidental injuries (23, 24). One way to potentially address this issue is through heat acclimatization. Gradual increases in the level of work performed in hot conditions lead to adaptations that enhance thermoregulatory mechanisms and heat tolerance, and ultimately this helps workers to work safely at heat levels that were previously intolerable (25, 26) and improve performance (26, 27).

Given that one bundle contains 20 stalks, a 1°C increase in heat stress could reduce output by about 4.2 bundles per worker per day, based on a rate of 9 stalks/

hour over 9.3 working hours. This negative effect of heat stress on productivity is consistent with previous research. Only one study in Thailand examined this relationship among sugarcane workers, reporting WBGT levels of 30.2–31.2°C and finding that higher bundle output was associated with lower WBGT (12). Radir et al (15) reported that each 1°C increase in WBGT reduced productivity by 6.6 bundles among sugarcane workers in Cambodia, although the number of stalks per bundle was not specified. Contextualizing the baseline temperature is crucial when comparing effect sizes across different agricultural settings. In our study, the estimated reduction of approximately 9 sugarcane stalks per hour for every 1°C increase applies to increases starting from our lowest observed empirical baseline of 22.9°C. In contrast, Hansson et al (28) studied sugarcane workers in Nicaragua and found that productivity among seed harvesters decreased by 3% for each degree Celsius increase in WBGT. Importantly, their reported productivity loss was calculated specifically for temperatures above a higher reference threshold of 28°C. This highlights how regional climate differences and baseline thermal variations can influence the magnitude of the reported dose–response relationship. Similarly, Dally et al (29), reported a median WBGT of 29.1°C (range 26.8–31.4°C) among Guatemalan sugarcane workers and observed reduced productivity (tons harvested per worker per day) with increasing WBGT.

Evidence from other agricultural settings supports these findings. Sadiq et al (16) reported WBGT values of 23–36°C at 06:00–15:00 hours among maize farmers in Nigeria and found that higher WBGT levels were associated with lower productivity, as measured by the number of ridges tilled or hoed per hectare. Another study by Sahu et al (22) on rice harvesters in India also found that the number of bundles decreased with increased WBGT (range 26–32°C). Additionally, work capacity declined by up to 27% with high heat exposure, as observed by Ioannou et al (30) in their study of grape-picking workers in Greece.

Other studies assessed heat exposure and productivity by looking at workers' perceptions, but this is a subjective measure. Pogačar et al (31) studied agricultural workers in Slovenia and found that heat stress exposure affected their productivity, as reported by 68% of the participants. Similarly, a study in India found that 70% of farm workers reported experiencing productivity loss due to heat stress exposure (32).

Although the current study found similar trends in the relationship between heat exposure and productivity as in previously mentioned studies, some differences should be noted. This study applied effective WBGT, which accounts for clothing, whereas previous studies (15, 16, 22, 28) considered only measured WBGT. This study measured productivity as the number of stalks har-

vested per worker per hour, which was counted by the researchers and cross-verified with the workers, whereas previous studies of sugarcane workers measured productivity by the number of sugarcane bundles loaded onto a truck, averaged per worker (15), or by the total number of bundles produced per day (28). Radir et al's study used direct observation to measure the production output during working hours (15), while Hansson et al's study used company records based on the supervisor's daily count, which serves as a highly accurate, mutually agreed-upon piece-rate payment metric for direct employees within a formal employment setting (28). Additionally, differences in populations, environments, and tasks in different studies led to varied effects of heat stress exposure on productivity. Future research could explore heat-induced productivity loss more broadly among other agricultural and outdoor workers. Longitudinal studies would also help identify the long-term effects of heat stress exposure and cumulative exposure on productivity over time.

The use of effective WBGT was chosen over ambient WBGT as it better represents the physiological thermal burden. A sensitivity analysis using ambient WBGT (supplementary table S6) showed a weaker, non-significant association with productivity, reaffirming the necessity of accounting for clothing adjustment values in agricultural heat stress assessments.

The productivity was assessed based on the number of stalks the workers harvested. However, it should be noted that the wage for harvesting burnt sugarcane is lower than that for harvesting unburnt sugarcane. Therefore, it would be helpful to consider productivity in relation to wages workers receive. The wage per sugarcane pile depends on the agreement between the farmers and the harvesters. These informal workers face greater financial and economic risks compared to other groups because their income is neither fixed nor guaranteed, and, most importantly, they are not covered by the minimum wage laws set by the Thai government (33).

Additionally, the number of stalks harvested per hour varied among the participants. Among the three main sugarcane harvesting methods, harvesting burnt sugarcane resulted in a higher harvest rate. This method is relatively uncomplicated, because it involves fewer steps than harvesting unburnt sugarcane, which requires removal of the leaves before cutting down the stalks. The descriptive information showed higher rate of sugarcane stalks during the hotter months. The likely explanation is that more sugarcane is burned during the hotter months in Thailand (7). A primary explanation is that sugarcane burning is heavily concentrated during these months, which coincide not only with Thailand's peak thermal period but also with the driest part of the year, which provides an important environmental prerequisite for effective burning. Furthermore, as demonstrated in

our previous work (7), farmers rely on burning due to distinct operational and economic drivers: reducing labor costs, easing harvesting when crops are damaged by wind or rain, managing accidental fires, and meeting tight delivery deadlines before sugar mill closures in late March. Consequently, higher productivity during hotter periods may be due to the easier harvesting of burnt sugarcane despite increased heat. However, no significant seasonal differences were observed after adjusting for confounders, possibly because data collection in cooler months occurred close to hotter months. Thus, the study may not fully represent the entire cool season (mid-October to mid-February), when temperatures are typically lower, especially in December and January.

While our broader research project has established the foundational health and physiological impacts of heat stress among Thai sugarcane workers (7, 9, 34), the current study explicitly isolates its significant impact on physical productivity. Future research should build upon these findings by integrating continuous monitoring of core body temperature and longitudinal assessments of kidney function (eg, evaluating renal biomarkers cross-shift and cross-harvest). Studying these specific parameters will elucidate the biological mechanisms linking heat stress, productivity loss, and kidney health, particularly given recent evidence demonstrating that repeated heat stress can rapidly trigger acute kidney injury (AKI) and progress to chronic kidney disease (CKD) (35). This will also allow for critical global comparisons with agricultural cohorts in Mesoamerica affected by chronic kidney disease of unknown etiology (CKDu).

Given the significant productivity decline with heat exposure, likely leading to income loss, practical workplace measures are essential, particularly in extreme heat. One potential intervention is modifying work schedules, such as implementing pre-dawn start times or split shifts (working during the early morning and late afternoon), to avoid peak midday heat while maintaining total daily working hours. While this approach could theoretically sustain both productivity and piece-rate income, its practical implementation in the Thai informal agricultural sector faces several logistical barriers. These include the lack of adequate artificial lighting for safe pre-dawn harvesting, transportation constraints, and the heavy morning dew on sugarcane leaves, which complicates cutting. To effectively mitigate heat impacts while safeguarding worker earnings in a piece-rate system, interventions should align with the occupational hierarchy of controls and encompass broader management system reforms. Beyond individual schedule modifications, workplace-level interventions, such as structured hydration and shaded rest protocols triggered by WBGT levels, are essential. Importantly, as demonstrated in Mesoamerican sugarcane cohorts by Hansson et al (35), sustained success requires institu-

tional changes in management practices. These include reforming informal contracting arrangements, optimizing supervisors' span of control, and integrating accountability for worker health outcomes into field operations. Combining well-designed rest and hydration programs with systemic administrative reforms offers a proven strategy to protect worker health while maintaining agricultural productivity.

Strengths and limitations

There were some notable strengths of the study. First, assessing productivity by counting the exact number of stalks harvested is a direct and precise method that yields reliable results. Heat stress measurements were carried out for a full work shift in both cooler and hotter seasons. There are also some limitations of this study. Some additional unmeasured confounding factors, such as heat acclimatization, variations in machetes used for harvesting, and machete sharpening, were not studied or included in the analysis and may have influenced the results. The cross-sectional nature of this observational study does not allow for full assessment of causal relationships. Additionally, the assessment of heat-related symptoms utilized a general 7-day recall period. While this effectively captured cumulative thermal strain and baseline heat susceptibility as a confounding factor, it did not explicitly isolate symptoms occurring solely on the measurement day. Therefore, we could not entirely rule out partial mediation effects. Future studies should separately assess acute symptoms experienced on the specific day of measurement versus historical symptoms to better disentangle confounding from causal mediation.

Concluding remarks

This study investigated the effects of heat stress exposure on productivity among Thai sugarcane workers and found that heat stress exposure significantly reduced the number of harvested sugarcane stalks. These findings highlight how rising heat stress exposure affects economic outcomes, especially for labor-intensive agricultural workers paid by the piece. Policymakers should develop and successfully implement targeted policies to support the well-being and productivity of informal agricultural workers. This would not only benefit the workers but also contribute to the country's gross domestic product (GDP). Ultimately, these results underscore the urgent need for workplace adaptations and interventions to mitigate heat-related risks as global temperatures continue to rise.

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Data availability

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

Conflicts of interest

The authors declare no competing interests.

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