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Physiological strain in outdoor workers: The hidden danger of high humidity

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ABSTRACT

Introduction: Outdoor workers in hot climates face significant heat strain, exacerbated by factors like air temperature and relative humidity (RH). While high temperatures' effects on health are well-documented, RH's critical role in influencing physiological strain is less explored. This study investigates RH's impact on the Physiological Strain Index (PSI) among outdoor workers, aiming to enhance safety in hot, humid conditions.
Methods: We conducted a cross-sectional study of 1452 outdoor workers across India (2014–2022), collecting data on air temperature, RH, wet bulb globe temperature (WBGT), and physiological heat strain indicators in the summer and winter. Generalised Linear Mixed Models (GLMM) and Generalised Additive Models (GAM) were utilised to assess RH's influence on PSI, potential non-linear relationships, and a heat-humidity threshold.
Results: Crude odds ratios (COR) indicated that workers exposed to high humidity were 2.5 times more likely to experience high PSI (COR = 2.5 [95 % CI: 1.82–3.44]). GLMM results confirmed RH's significant impact on PSI when adjusting for covariates (aOR = 1.6 [95 % CI: 1.24–2.29]). GAM analysis revealed non-linear relationships between air temperature, RH, and PSI. The predictive model derived from the GAM identified a heat-humidity threshold of 32 °C and 60 % RH.
Discussion: Elevated PSI under high humidity conditions highlights the need for tailored protective measures, such as hydration strategies and adjusted work-rest cycles, to mitigate physiological strain in hot and humid environments.
Conclusion: RH significantly exacerbates PSI among outdoor workers. These findings inform workplace safety guidelines, emphasizing the need for more aggressive heat stress management in high-humidity conditions.

1. Introduction

The mean surface temperature and frequency of extreme heat events have risen consistently in the past few decades, impacting numerous industries, particularly in low- and middle-income countries (Rao et al., 2023). Climate change is a key driver, contributing to approximately 37 % of heat-related mortality in 43 nations since 1991, with further increases projected as global temperatures continue to rise (Vicedo-Cabrera et al., 2021). These temperature extremes pose significant public health challenges, as prolonged exposure leads to increased morbidity and mortality globally. Increased water vapour is directly related to increased surface temperatures (Khan et al., 2022). This is especially pertinent to South Peninsular India where the northeast monsoon brings north-eastward winds from the Bay of Bengal that carry a significant amount of water vapour to coastal Andhra Pradesh, Rayalaseema, Tamil Nadu, and Pondicherry from October to December (Khan et al., 2022). This can be seen in other parts of India as well, for example, the severe impact of extreme heat was evident in India during the 2024 early summer heatwave, which claimed over 733 lives and caused over 40,000 cases of heatstroke in 17 states. In New Delhi, temperatures soared over 50 °C and surpassed 45 °C in 37 other cities (Zargar, 2024).

Heat stress is defined as the physiological strain encountered by workers as a result of elevated environmental temperatures leading to reduced physical labour capacity and related health risks (Collier et al., 2018). The condition resulting from the body's inability to maintain thermal equilibrium can be classified as dry or humid depending on ambient humidity levels (Sojan and Srinivasan, 2024). Dry heat stress,

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caused by low humidity and high temperatures, can typically be managed with heat action plans (HAPs) and hydration. However, humid heat stress – arising from high temperatures coupled with elevated humidity – presents a more dangerous scenario (Ioannou et al., 2021). Under such conditions, the body's natural cooling mechanisms, like sweating, are significantly impaired, leading to an increased risk of heat-related illnesses (HRIs). Thermo-homeostasis, the process by which the body regulates its core body temperature (CBT), becomes compromised when the ambient temperature exceeds the body's thermal comfort threshold, especially in humid environments (Sojan and Srinivasan, 2024).

An ambient temperature of 37 °C may be tolerable under low humidity conditions, the combination of high humidity and stagnant air can restrict the body's ability to dissipate heat, potentially resulting in severe health risks (Huang et al., 2023). Heat stress cannot be attributed to temperature alone; it is the result of complex interactions between various meteorological factors – such as humidity, wind speed, and prior heat exposure – as well as individual characteristics such as clothing, metabolic rate, and acclimatization (Cvijanovic et al., 2023). Consequently, certain populations, including the elderly, individuals with chronic health conditions, migrants and outdoor workers, as particularly vulnerable to heat stress (Parsons et al., 2022). Among them, outdoor and migrant workers in India's vast informal sector face an elevated risk of physiological strain due to their continuous exposure to extreme weather and engagement in physically demanding work (Venugopal et al., 2015). India's informal sector accounts for nearly 90 % of its total workforce, with over 450 million people engaged in agriculture, construction, brick kilns, salt pans, and other labour-intensive outdoor occupations (Raveendran and Vanek). A lack of automation in these industries means that over 85% of tasks still rely on manual labour, intensifying workers' exposure to extreme heat and increasing their risk of HRIs and productivity loss (Hammer and Karmakar, 2021) Moreover, prolonged exposure without adequate cooling, hydration, or rest breaks, exacerbates their vulnerability to HRIs and productivity loss, as the combined effects of high temperature and humidity severely impair the body's ability to regulate heat (Kjellstrom et al., 2016; Cramer et al., 2022).

Despite the well-established understanding of the biophysiological mechanisms underlying heat stress, relatively few studies have quantified how humidity interacts with heat to increase the probability of increased physiological strain. Most studies on occupational heat stress have focused on dry heat environments, particularly in regions like the Middle East and Australia, where humidity is lower, but temperatures are extreme (Jay and Brotherhood, 2016; Kjellstrom, 2009; Spector et al., 2019; Oppermann et al., 2017; Amoadu et al., 2023). However, there is a notable gap in research on compound heat events – situations where high temperatures coincide with high humidity, common in tropical and subtropical regions.

In this study, we focus on the critical role of relative humidity (RH) – the ratio of the current amount of water vapour in the air to the maximum amount it can hold at the same temperature – and its interaction with high temperatures (Vanos et al., 2012). Understanding the intricate relationship between high temperatures and humidity is crucial, especially in the context of India, where regions with humidity often coexist with high temperatures. This nuanced understanding is critical in developing more accurate risk assessments, as humidity can greatly amplify the physiological burden of heat exposure, even in conditions where temperatures alone might not pose an immediate danger. These findings are essential for creating more effective HAPs and occupational safety guidelines.

By utilising statistical models such as generalised additive models (GAM), this study captures the nonlinear and compounding effects of these variables. The novelty of this approach lies in its ability to identify thresholds at which high humidity begins to significantly worsen health outcomes, thus offering new insights into mechanisms driving HRIs that go beyond conventional heat stress research.

2. Methods

2.1. Study design and population

This study investigated the impact of heat and humidity on physiological strain in outdoor workers. We collected data from 1452 outdoor workers across 35 workplaces in five industries in central and southern India (2014–2022). These included Agriculture, Brick Kilns, Construction, Fisherman, and Salt Pans. Data collection took place in two distinct seasons, the hotter season (April–June) and the cooler season (November–January) thereby capturing seasonal variations. However, the analysis was not stratified by season. Instead, we examined the impact of humidity on physiological strain across the entire dataset, independent of seasonal differences.

This study was conducted after obtaining ethical clearance from the Sri Ramachandra Institute of Higher Education and Research (SRIHER) Institutional Ethics Committee (REF: IEC-NI/12/OCT/30/57) and the study was conducted in compliance with the ethical standards as established in the 1964 Declaration of Helsinki. Additionally, we obtained authorisation from workplaces to perform the study. Outdoor workers were selected according to the criteria of being of the ages between 18 and 60 and having experienced heat exposure at the same employment for a minimum of one year. Individuals above the age of 60 were excluded to minimize confounding from age-related comorbidities, ensuring clearer attribution of outcomes to heat exposure. Individuals with pre-existing medical issues including diabetes, hypertension, heart disorders, thyroid ailments, or any comorbidities, were excluded from the study. Prior to inclusion in the study, we obtained informed consent from all participants post explaining the study's objectives, procedures, risks and benefits.

2.2. Data collection

Participants were recruited from four key occupational sectors: agriculture, brick kilns, construction, and salt pans. These industries were selected based on prior research indicating high susceptibility to heat strain due to prolonged outdoor work and exposure to both high temperatures and humidity. The sample distribution across sectors was not pre-stratified but instead reflected workforce availability and accessibility during recruitment. The sample size was calculated based on Venugopal et al., 2016, with an assumed prevalence of 32% for heat stress exposure, a 95% confidence level, and a precision of 2.5%. This resulted in an estimated sample size of 1337 participants to ensure sufficient power for detecting statistically significant associations.

Data on heat stress exposure – including air temperature, RH, wind speed, and WBGT – were measured using the Wet Bulb Globe Temperature (WBGT) monitor and a portable heat stress meter (QuesTemp 34; QUEST Technologies, Oconomowoc, WI, USA, USA. Model no. TEM: 090017). This monitor provides an accuracy of 0.5°C between 0 and 120°C dry bulb temperature and 5% RH. All measurements were taken at hourly intervals during standard working hours respective to the workplace. Air temperature and RH measures were taken between 10 a.m. and 4 p.m., except for the brick industry, whose standard working hours started at 4 a.m. The frequency of measurements varied based on workload and probable heat exposure zones. We took multiple hourly measurements throughout the day, however, the frequency differed based on employees' work intensities and potential zones of heat exposure. All evaluations were conducted in each location over one to three days consecutively.

Physiological heat strain indicator measures included the CBT, sweat rate (SwR), heart rate, and urine specific gravity (USG). CBT was measured using a Rossmax digital infrared ear thermometer which captured tympanic temperature, a slightly better estimator of body temperature when compared to other thermometric methods as a proxy for CBT (Pecoraro et al., 2021). For increased reliability, three consecutive readings were taken and averaged for each measure. SwR was assessed by calculating the difference between pre- and mid-shift measurements throughout the observation period, divided by self-reported fluid intake utilising the Canadian Sports Association technique (Venugopal et al., 2024). USG was ascertained using a clinical portable ATC urine refractometer using urine samples that were collected before work and lunch. USG was used to assess hydration status. An increase in CBT >1°C, SwR > 1L/hr, and USG >1.020 were classified as unsafe (Venugopal et al., 2023).

2.3. Statistical analysis

All analyses were performed using R (version 4.4.2). The data distribution was verified using descriptive statistics, specifically, summary statistics tables and boxplots, which served as the foundation for the identification of outliers, these can be found in Appendix Figure A. We eliminated anomalies below a confidence interval of 85%, as well as CBT which was three standard deviations from the mean. Three data points were identified as outliers and subsequently removed from the dataset. Additionally, 5% of the data were eliminated due to missing information, resulting in a final sample of 1452 participants included in the complete case analysis.

The Physiological Strain Index (PSI) was calculated using custom functions, and both linear and non-linear modelling approaches were implemented to rigorously investigate the relationships between heat, humidity, and physiological strain. PSI is a comprehensive measure that captures both thermal and cardiovascular strain, providing a combined view of the body's response to heat exposure by accounting for changes in CBT and heart rate. This is suitable for assessing physiological strain in high-heat conditions, offering a holistic view of the body's response that a single measure alone might not capture.

2.3.1. Physiological Strain Index calculation

To quantify physiological strain, the PSI was calculated using the formula obtained by Moran et al. (1998) (24):

$$PSI = 5(CBT_t - CBT_0)(39.5 - CBT_0)^{-1} + 5(HR_t - HR_0)(180 - HR_0)^{-1}$$

Where CBT_t and HR_t are the final CBT and heart rate at time t_1 and CBT_0 and HR_0 represent baseline values measured at the start of the work shift. The value of 39.5°C is the upper bound for CBT and 180 beats per minute (bpm) is the upper bound for heart rate according to Moran et al. (1998). The value of five is the weight of every physiological parameter in the calculation of PSI. This formula accounts for both thermal and cardiovascular strain induced by heat exposure (Moran et al., 1998).

2.3.2. Investigation of interaction and threshold effects

First, we assessed for potential threshold effects by categorising air temperature and RH into high and low levels. Workers were classified as:

1. High temperature with high humidity (HTHH): Air temperature >32°C and RH > 60 %
2. High temperature with low humidity (HTLH): Air temperature >32°C and RH < 40 %

The temperature of 32°C was identified as a high temperature in an occupational setting by Morrissey et al. (2021a,b), and RH boundaries of 40% and 60% by Watson et al. (2011) (26). A two-sample *t*-test was used to compare the mean PSI between these two temperature-humidity groups.

2.3.3. Generalised linear mixed models

To examine the relationship between air temperature, RH and PSI, we first fit a generalised linear mixed model (GLMM) with random intercepts per participant to account for repeated measures per participant. This model allowed for individual variation in baseline physiological strain while estimating the effects of air temperature, humidity, and their interaction on PSI. The model also accounted for potential confounding factors by including covariates such as sex, age, drinking status, smoking status, and metabolic rate. However, WBGT was not included as a predictor in out models, due to its strong correlation with RH, which could lead to collinearity concerns. Instead, we focussed on RH as an independent variable to specifically assess its contribution to physiological strain. The GLMM was fitted with a log-link function to account for the continuous nature of PSI and handle the skewness in the data. The model fit was evaluated using AIC and BIC, and the model with the lowest values was selected.

2.3.4. Generalised additive models and non-linear relationships

Given the potential non-linear relationships between environmental factors (e.g., air temperature, and RH) and PSI, we extended our analysis using generalised additive models (GAM). The GAM approach allowed flexible, non-linear smoothing functions to model the relationships between air temperature, RH, and PSI without assuming a strictly linear interaction. Smoothing splines were applied to both air temperature and RH, and the model's degrees of freedom were selected through cross-validation to avoid overfitting. Model fit was similarly assessed through AIC and cross-validation performance metrics to confirm the suitability of the non-linear modelling approach. The lme4 package was used for mixed effects modelling and the mgcv package for generalised additive modelling.

The GLMM was used to account for individual-level variability in physiological responses, providing a robust understanding of the fixed effects of temperature and humidity across the population. Meanwhile, the GAM allowed us to model non-linear relationships between environmental conditions and physiological strain, revealing complex interactions and thresholds that inform occupational risk more accurately.

3. Results

3.1. Descriptive statistics

A total of 8518 observations across 1452 participants were analysed. The study population was primarily composed of individuals working in agriculture (29.7%), brick kilns (18.9%), construction (17.3%), salt pans (25.7%), and fishermen (8.1%). The average age of the participants was 42.2 years with 45.2% of the sample being male and 68.5% reporting alcohol consumption. Physiological strain indicators such as CBT, heart rate, and urine-specific gravity (USG), were used to assess hydration status and overall strain. The mean CBT was 37.1°C while the average heart rate was 84 bpm.

Environmental conditions varied considerably across the study with air temperatures ranging from 21.5°C to 43.0°C and RH between 28.5% and 88%. Wind speeds ranged from 0 to 6.3 m/s, with an average of 1.38 m/s. The WBGT had a mean value of 29.3°C, indicating significant heat stress potential for outdoor workers in these environments. These

Table 1
Descriptive statistics for all continuous variables.

Variable	Mean	SD	Minimum	Maximum
Socio-demographic Information				
Age	42.2.27	12.97	18	60
Environmental Conditions				
Air Temperature (°C)	30.23	3.56	21.50	43.00
Relative Humidity (%)	50.52	12.27	28.50	88.00
Wind Speed (m/s)	1.38	1.08	0	6.30
Wet Bulb Globe Temperature (WBGT)	29.30	2.96	20.30	41.60
Physiological Strain Indicators				
Core Body Temperature (CBT) (°C)	37.11	0.47	36	38.5
Heart Rate (bpm)	84.62	9.49	60	164
Sweat Rate (L)	0.52	0.35	0.1	1.9
Urine specific gravity	1.01	0.6^{-2}	1.003	1.04

results can be found in Tables 1 and 2.

3.2. Physiological Strain Index and environmental conditions

Workers were categorised into two groups based on air temperature and humidity thresholds: high air temperature with high humidity ($n = 202$) and high air temperature with low humidity ($n = 1032$). A two sample *t*-test indicated a statistically significant difference in mean PSI between workers exposed to HTHH versus HTLH conditions (mean PSI $= 2.28$ vs 2.01, $t(1232) = -7.25$, $p < 0.001$).

To further investigate the risk of high physiological strain (PSI > median) in different humidity conditions, a binary logistic regression was conducted which yielded a crude odds ratio of 2.51 (95% CI: 1.82–3.44) for PSY in workers exposed to high humidity (>60%) versus low humidity (<40%) at air temperatures above 32°C, indicating that workers exposed to high humidity were 150% more likely to experience elevated physiological strain compared to those in low humidity conditions. This association was statistically significant ($p < 0.001$).

3.3. Generalised linear mixed model

A GLMM with random intercepts per participant, to account for repeated measures, was employed to examine the interaction between air temperature and RH on physiological strain. The model identified a significant interaction between air temperature and RH ($p < 0.01$), highlighting the multiplicative effect of high temperature and high humidity on physiological strain. Specifically, at temperatures above 32°C, each 10 % increase in RH resulted in a 22% greater increase in PSI compared to low RH conditions (OR for the interaction = 1.22; 95% CI: 1.10–1.35, $p < 0.01$). Wind speed (OR = 1.15; 95% CI: 1.10–1.20, $p < 0.001$) and drinking status (OR = 1.42; 95% CI: 1.24–1.63, $p < 0.001$) were also found to have a significant effect on PSI. Metabolic rate showed a protective effect on PSI (OR = 0.64; 95% CI: 0.52–0.78, $p < 0.001$). The results can be found in Table 3.

3.4. Generalised additive model

A GAM was used to explore potential non-linear relationships between air temperature, RH, and PSI. The results demonstrated significant non-linear effects of both air temperature and RH on PSI ($p < 0.001$ for both). The output results can be found in Appendix table A. The predicted probability of experiencing high physiological strain increased with higher air temperatures and was further exacerbated by higher RH. A complete heatmap illustrating the predicted probability of physiological heat strain at various temperature humidity combinations can be found in Appendix Figure B. The visualization in Fig. 1 illustrates the predicted probability of experiencing high PSI as a function of air temperature and RH.

Table 2
Descriptive statistics for all categorical variables.

Variable	Category	Count (*n*)	Percent (%)
Socio-demographic Information			
Sex	Male	657	45.23
	Female	795	54.77
Alcohol consumption	Yes	995	68.51
	No	457	31.49
Smoking Status	Smoker	1138	78.37
	Non-smoker	314	21.63
Industry	Agriculture	432	29.72
	Construction	252	17.32
	Brick Kilns	275	18.99
	Salt Pan	375	25.86
	Fisherman	118	8.11
Physiological Strain Indicators			
Dehydration Status (USG >1.020)	Dehydrated	912	62.85
	Not dehydrated	540	31.75

Table 3
Output and p-values for the generalised linear mixed model with random intercepts per participant.

Variable	OR Estimate (95 % CI)	*p*-value
High air temperature - High relative humidity[a]	1.67 (1.23–2.28)	<0.001
High air temperature - Low relative humidity	1.06 (0.96–1.17)	0.25
Wind speed (per 1 m/s increase)	**1.15 (1.10–1.20)**	**< 0.001**
Age (per year increase)	1.09 (0.93–1.19)	0.09
Sex		
Female	–	–
Male	1.07 (0.95–1.19)	0.24
Metabolic rate		
180 W (Reference)	–	–
415 W	0.64 (0.52–0.78)	<0.001
Smoking habit		
Non-smoker	–	–
Smoker	1.02 (0.89–1.17)	0.70
Alcohol consumption habit		
Non-drinker	–	–
Drinker	**1.42 (1.24–1.63)**	**< 0.001**

[a] Reference category: Low air temperature - Low relative humidity. Odds Ratios (OR) represent the effect of high air temperature with different humidity conditions relative to this baseline.

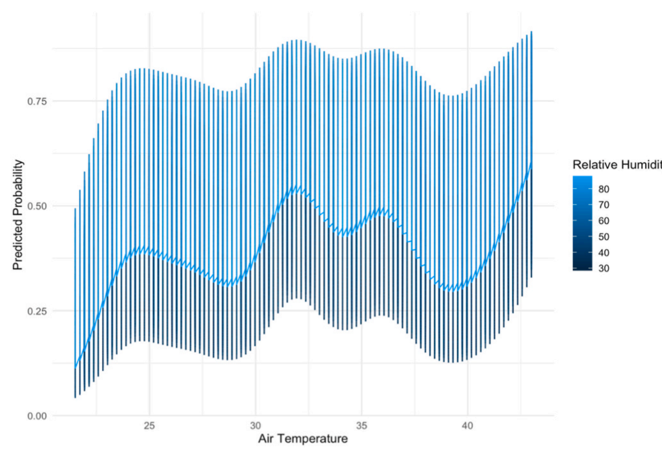

Fig. 1. Predicted probability of high physiological strain by air temperature and relative humidity according to the generalised additive model.

The figure illustrates that at high air temperatures, increasing RH significantly amplifies the probability of a high PSI. At 32°C, the predicted probability of a high PSI increases from 0.30 at RH < 40% to 0.75 at RH > 80%. At 35°C, the probability rises from 0.50 at RH < 40% to 0.85 at RH >80%, demonstrating the compounding effect of humidity on heat strain risk.

Several key inferences can be made from the predictive model illustrating physiological strain due to temperature and humidity. First, it is apparent that LTHH still elevates the risk of physiological strain. Even at lower temperatures (25–30°C), the predicted probability of high PSI is elevated when relative humidity exceeds 60 %. Upon visual inspection, the slope of increasing PSI in this temperature range is quite steep indicating that the physiological burden accelerates rapidly as humidity climbs.

Second, there appears to be a threshold at 32°C, acting as a critical turning point for physiological strain when humidity increases. At all values of RH, the probability of PSI increases sharply at 32°C, however, at 60% RH, there is a significant climb in the PSI – therefore, 32°C and 60% RH can be considered a threshold level for dangerous climactic conditions for outdoor workers in South Indian climatic scenario.

Third, high humidity significantly amplifies the risk of PSI at higher temperatures. The interaction of RH and air temperature is particularly evident in the upper ranges of both variables – specifically at temperatures between 35°C and 40°C, the predicted probability of high PSI increases dramatically when RH exceeds 70%. Table 4 presents the predicted probability of high physiological strain across air temperature and RH levels. The model shows that RH significantly amplifies PSI risk, particularly beyond 32°C, where high humidity (>60%) disproportionately accelerates the probability of physiological strain corroborating Fig. 1.

The relationship between RH, temperature, and physiological strain follows a complex non-linear trend, There are notable dips and elevations at specific points in the temperature-humidity interaction. The model shows dips in the predicted probability around 27°C and 35°C, followed by subsequent rises.

4. Discussion

This study investigated the combined effect of temperature and humidity on physiological strain across 1452 outdoor workers across various sectors, including agriculture, construction, salt pans, fishing, and brick kilns in South India. As climate change continues to increase global temperatures, vulnerable populations, particularly outdoor labourers, face substantial heat-related health risks due to prolonged exposure to high temperatures and humidity (Parsons et al., 2022).

4.1. Key findings and their implications

This study's findings highlight that both air temperature and humidity play a substantial role in determining physiological strain, as measured by the PSI. The results of the two-sample *t*-test demonstrate the importance of humidity in exacerbating physiological strain, with workers in HTHH conditions experiencing a modest, however, statistically significant increased physiological strain compared to those in HTLH environments (mean PSI difference: 0.27, $p < 0.001$). This indicates that even small increases in physiological strain can have significant health impacts, particularly in prolonged exposure scenarios. The logistic regression further underscores this, with workers in high humidity (>60 %) conditions being twice as likely to experience elevated psychological strain. Given that PSI is a composite measure of thermal and cardiovascular strain based on CBT and HR, these findings reinforce that high humidity accelerates the onset of physiological burden by impairing the body's evaporative cooling capacity through sweating, a critical mechanism in thermoregulation, thus posing heightened risks for outdoor workers in physically demanding jobs. This is especially relevant for the agriculture, construction, and salt pan industries which are labour-intensive in open-air environments (Parsons et al., 2022). USG and SwR were analysed separately as hydration indicators and were not included in PSI calculations.

Our results suggested that high HTHH conditions pose a much greater risk to human health than HTLH. This was demonstrated by both models used in this analysis, the GAM and GLMM as they provided varying perspectives on the compounded impact of the two meteorological variables on physiological strain. We identified a threshold of 32°C and 60% RH as a heat-humidity threshold with the use of a GAM. The GLMM found that at temperatures above 32°C, a linear interaction took place with a 22% increase in PSI for every 10% rise in RH. This delivers a definitive and actionable message for policymakers This finding demonstrates that high humidity does not simply add to the burden of heat stress, but interacts synergistically with high air temperatures to produce disproportionally higher levels of heat strain, suggesting that even little increases in humidity can yield significant consequences when temperatures are already high (Xu et al., 2025).

Table 4
The predicted probability of high physiological strain across air temperature and RH levels.

Air temperature (°C)	RH < 40 %	RH 40–60 %	RH > 60 %	RH > 80 %
25	~0.10	~0.15	~0.20	~0.25
30	~0.20	~0.30	~0.45	~0.55
32	~0.30	~0.45	~0.60	~0.75
35	~0.50	~0.60	~0.75	~0.85
40	~0.65	~0.75	0.85	~0.95

The GLMM results provide a deeper insight into the interaction between temperature, humidity, wind speed, and individual characteristics. The significant interaction between air temperature and RH ($p < 0.01$) had a multiplicative effect on physiological strain – every 10% increase in RH, led to a 22% rise in physiological strain when air temperature exceeded 32°C. Additionally, higher wind speeds were associated with increased physiological strain (OR = 1.15; 95% CI: 1.10–1.20), which may seem counterintuitive. While wind speed enhances evaporative cooling, it may be reflective of more extreme weather conditions where the benefits of increased airflow are offset by higher ambient temperatures and humidity, leading to increased PSI (Baldwin et al., 2023). Furthermore, wind transports hot air, further limiting its cooling capacity in already high-heat environments (Stasi et al., 2024).

Metabolic rate, conversely, exhibited a protective effect on PSI (OR = 0.64; 95% CI: 0.52–0.78, $p < 0.001$), suggesting that individuals with higher metabolic dissipate heat more effectively due to increased cardiovascular efficiency and muscle heat generation thereby improving resilience to heat stress (Parsons et al., 2019). However, this protective effect may have limits and be limited to certain levels of exposure, as sustained high temperatures and humidity can overwhelm even those workers with higher metabolic efficiency.

While the GLMM quantified the overall risk, the GAM offered a more intricate understating of the non-linear interaction between temperature and humidity. The identified threshold– 32°C and 60% RH – highlights a critical point beyond which thermoregulatory mechanisms become inefficient. The threshold represents a significant escalation point for physiological strain, indicating that high humidity acts as a critical multiplier of heat stress. This threshold is lower than the conditions deemed safe by the ISO 7243 standard, which sets a WBGT limit of 30°C for heavy work in humid conditions (International Organization for Standardization, 2017). Our findings suggest that workers in hot-humid environments are at risk even when ambient temperatures are within what current standards may consider tolerable. Further investigation under controlled conditions is necessary due to the numerous variables, including individual variabilities in field conditions that may affect the outcomes (Parsons et al., 2022).

Additionally, the GAM revealed non-linear fluctuations in physiological response, particularly at 27°C and 35°C, indicating an inconsistent physiological response to heat and humidity, where temporary adaption may occur before stress escalated to elevated levels. These fluctuations warrant further investigation to elucidate the underlying mechanisms and their potential implications for worker protection.

While WBGT is a widely used heat stress index that incorporates temperature humidity, wind speed, and solar radiation, it does not allow for the independent assessment of humidity's contribution to physiological strain. Since RH and WBGT were highly correlated in our dataset, including both in the models would have introduced collinearity, potentially obscuring the specific effects of humidity. Given that evaporative cooling is less effective in humid conditions, WBGT may underestimate physiological stress in such environments. This distinction is particularly important in understanding heat stress in tropical climates, where humidity-driven physiological strain may be underestimated in standard heat stress indices (Vanos and Grundstein, 2020).

This study's findings are in line with previous research on heat stress and provide added depth by focusing on the compounded effect of high humidity and temperature. Studies on heat-related health outcomes frequently overlook the role of humidity in exacerbating heat stress. Barreca (2012) identified that high specific humidity (SH) has a small adverse impact on mortality in the United States, however, our study's focus on physiological strain adds an additional layer of insight into how these meteorological factors affect workers in tropical climates (Barreca, 2012). Moreover, previous studies such as those by Rocklöv and Forsber (2010) report a significant impact of RH on heat-related mortality, particularly in northern European countries (Armstrong et al., 2019). However, our study's findings for southern India illustrate that the impact of RH on physiological strain is even more pronounced in warmer regions, which supports the need for region and work sector-specific interventions.

The absence of explicit national regulations mandating work stoppages at certain temperature thresholds underscores the need for region-specific heat protection policies. India's legal framework for occupational safety and health includes the Factories Act of 1948 and the Occupational Safety Health and Working Conditions Code (2020) (Ansari, 2020). While these laws broadly address workplace safety, they do not specify mandatory work halts for extreme heat exposure. While some local authorities issue advisories during heatwaves, these measures are inconsistent and do not account for the heightened physiological strain caused by high humidity (Dehury, 2017). Given our findings, policymakers must integrate humidity-adjusted thresholds into heat action plans (HAPs) and occupational safety guidelines. Industries such as – agriculture, brick kilns, construction, and salt pans – require specific protections and are at extreme risk of HRIs when this threshold is breached.

Given that high-humidity environments significantly amplify physiological strain at lower temperatures, tailored strategies are essential. While revising occupational safety, integrating humidity-adjusted thresholds into occupational safety standards (e.g., ISO 7243, WBGT) is necessary, immediate workplace interventions can enhance worker protection (Barreca, 2012). Unlike dry heat conditions, where the body can effectively cool itself through sweating and evaporation, high humidity limits evaporative cooling, causing heat to accumulate and increasing the risk of heat strain (Morrissey et al., 2021b). Consequently, interventions must focus on alternative cooling methods that do not rely solely on sweat evaporation. Personal cooling vests with phase-change materials or cooling towels applied to pulse points (e.g., neck, wrists) provide direct cooling without depending on sweat evaporation (Hossain et al., 2024). These interventions are particularly relevant for brick kiln and salt pan workers who experience direct heat exposure from the ground and surrounding surfaces. Additionally, airflow optimisation using portable fans or natural ventilation can enhance convective heat dissipation, helping to offset the reduced effectiveness of sweating in humid conditions (Suen et al., 2021). This may be especially beneficial in construction settings, where stagnant air between structures, exacerbates heat build-up.

Since excessive sweating in humid environments can lead to dehydration and salt loss, oral rehydration salts (ORS) or electrolyte-enhanced drinks should be provided alongside plain water (Yi et al., 2016). While adequate hydration remains critical, electrolyte supplementation is necessary to prevent hyponatremia, a condition where excessive water intake dilutes essential sodium levels (Glaser et al., 2022). In agricultural work, where prolonged exposure and high physical exertion increase fluid loss, hydration stations with electrolytes should be placed at accessible locations in the fields. Workers should also be encouraged to monitor urine colour or body weight changes to detect early signs of dehydration before symptoms of HRIs develop.

Work-rest cycles should also be adjusted to reflect the physiological challenges of high humidity. In contrast to dry heat environments, where longer work intervals may be sustainable with proper hydration, high humidity increases cardiovascular strain and impairs the body's ability to recover (Habibi et al., 2024). Therefore, shorter, more frequent rest breaks (e.g., every 45 min instead of hourly) should be implemented, with rest occurring in well-ventilated or shaded areas to facilitate passive cooling (Bodin et al., 2016). For construction and brick kiln workers, shaded break areas or portable cooling shelters should be installed to ensure access to cooling spaces. In salt pans, rest breaks should align with peak humidity periods so minimize heat strain during the most critical exposure windows. Additionally, humidity-sensitive early warning systems such as real-time monitoring of ambient humidity and worker physiological responses can help workplaces implement dynamic rest schedules based on actual risk levels rather than static health thresholds (Yi et al., 2016).

Since humidity also affects clothing choices, standard recommendations for heat stress mitigation must be adapted. Clothing should be moisture-wicking and loose fitting to reduce thermal burden, unlike heavy cotton fabrics that trap sweat and prevent airflow (Chan et al., 2016). This is particularly relevant for agricultural workers, who often wear traditional, layered clothing for sun protection but may require lightweight alternatives that balance coverage with ventilation. Encouraging workers to wear lightweight breathable materials can enhance convective cooling, which becomes the dominant cooling mechanism when evaporative cooling is impaired.

These practical, humidity-specific interventions – alternative cooling methods, electrolyte supplementation, adjusted work-rest cycles, airflow optimisation, and clothing modifications – complement broader policy changes and offer a comprehensive strategy to mitigate the risks of humidity-exacerbated heat strain in outdoor workers.

While this study focused on the impact of humidity on physiological strain, future research could explore temporal trends in heat stress across multiple years. Given the increasing frequency of extreme heat events and challenging climate conditions, analysing long-term variations in physiological strain could provide valuable insights into adaptation patterns, workplace interventions, and emerging risks for outdoor workers.

4.2. Strengths and limitations

The first strength of this study is that a sample size of 1450 participants analysed across five sectors allowed us to capture various environmental parameters varying by sector-specific factors such as workload, and range of physical motion, augmenting the generalizability of our findings. Second, the statistical analysis techniques employed, i.e., the GLMM and GAM, enabled us to capture both linear and non-linear effects of the exposures and outcome interactions, allowing a robust analysis. Third, this study provides insight into a complex relationship between temperature and humidity in a region significantly affected by humid heat conditions. By analysing data from South India, we provide insights that are directly applicable to a country where over 450 million people work in the informal sector, many of whom are exposed to extreme environmental conditions.

The study has a few limitations. First, this study did not assess cumulative exposure or the long-term effects due to the cross-sectional study design, longitudinal studies are more suited for that purpose. Second, the measure of humidity analysed in this paper is relative humidity, which might have been inappropriate compared to mass-based measures of humidity such as absolute humidity, specific humidity or the dew point temperature (Baldwin et al., 2023). In the context of heat and health, the gradient of water vapour between skin and air drives sweat evaporation; therefore for evaluating its health impacts, water vapour mass-based variables are the most pertinent indicators concerning human thermoregulation, not RH (Davis et al., 2016).

5. Conclusion

This study underscores the significant impact of compounded high air temperatures and relative humidity on physiological strain among outdoor workers in India. We identified a temperature-humidity threshold beyond which the risk of HRIs increases significantly highlighting the importance of considering both temperature and humidity when assessing heat-related health risks, as current indices tend to oversimplify these complex relationships and risk masking dangerous environmental conditions in occupational settings. The findings underscore the need for occupation and region-specific interventions.

Policymakers must integrate these insights into HAPs and occupational safety protocols emphasizing real-time environmental monitoring, education on heat stress prevention, and workplace adjustments. Additional studies in environmental chambers under controlled conditions are necessary to draw robust conclusions regarding the optimal temperature and relative humidity thresholds for safe work.

CRediT authorship contribution statement

Tanya Isaac: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Formal analysis, Data curation. **S. Ranjith:** Methodology, Data curation. **P.K. Latha:** Writing – review & editing, Project administration, Methodology, Investigation, Funding acquisition, Conceptualization. **Rekha Shanmugam:** Writing – review & editing, Project administration, Methodology, Investigation. **Vidhya Venugopal:** Writing – review & editing, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization.

Data statement

The datasets used and analysed during the current study are available from the corresponding author upon reasonable request.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envres.2025.121495.

Data availability

Data will be made available on request.

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