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Assessment of Heat Stress in Iranian Industries and Temporal Trends over the Last Two Decades: A Systematic Review and Meta-Analysis

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Abstract

Heat stress is a major occupational hazard threatening workers' health, safety, and productivity. This study aimed to estimate pooled mean Wet Bulb Globe Temperature (WBGT) across industries in Iran and assess temporal trends over the past two decades. This systematic review and meta-analysis followed PRISMA guidelines. Web of Science, Scopus, PubMed, Science Direct, IranMedex, Magiran, Google Scholar, and SID were systematically searched through December 31, 2023. Eligible studies were conducted in Iran and assessed occupational heat stress using WBGT. Study quality was evaluated using the JBI checklist. Random-effects meta-analysis and meta-regression were performed using STATA 17. Of 593 records identified, 43 studies were included (19 open and 24 roofed environments). Pooled mean WBGT was 25.71°C (95% CI: 23.36–28.06) in open and 28.11°C (95% CI: 25.88–30.34) in roofed environments, with substantial heterogeneity ($I^2 > 99.9\%$). Industry type explained 85.66% and 41.12% of heterogeneity, respectively. The highest WBGT occurred among date-harvesting workers (33.20°C) and in the steel industry (40.20°C). WBGT increased significantly over time in open environments ($\beta=0.68$, $p=0.0248$), but not in roofed environments ($p=0.3392$). Occupational heat stress in Iran is substantial, particularly in hot industries and tropical regions. The increasing WBGT trend in open environments underscores the need for climate-adaptive occupational heat-management strategies.

Keywords: Heat stress, Thermal stress, Wet bulb globe temperature, WBGT, Iran, Meta-analysis

1. Introduction

Heat stress is recognized as one of the most important and common physical hazardous agents in workplaces, posing a serious threat to the health, safety, and productivity of the workforce [1]. This phenomenon occurs when the balance between heat produced by the body (due to metabolism) and heat received from the environment with heat dissipated from the body is disrupted. As a result, core body temperature increases and compensatory physiological responses such as increased heart rate, sweating, and peripheral vasodilation occur [2, 3]. If exposure continues and the thermoregulatory system fails, complications such as muscle cramps, heat exhaustion, heat syncope, and in severe cases, heat stroke (a life-threatening condition) develop [4]. Accurate assessment of heat stress in workplaces is the first step in managing and controlling this occupational hazard. Among more than 60 indices proposed for assessing heat stress over the past century, the Wet Bulb Globe Temperature (WBGT) index, due to its comprehensiveness, relative ease of measurement, and endorsement by reputable international authorities, has been introduced as the gold standard and the most widely used index worldwide [5, 6]. This index, first developed by Yaglou and Minard in 1957 for the US Navy, is a weighted combination of three environmental parameters: natural wet-bulb temperature (indicating humidity and evaporative cooling potential), globe temperature (indicating radiant heat), and dry-bulb temperature (indicating air temperature) [7]. The International Organization for Standardization (ISO) in standard 7243 and the American Conference of Governmental Industrial Hygienists (ACGIH) have respectively developed the measurement method and exposure limit values for heat stress based on this index [8, 9]. The Islamic Republic of Iran, with its vast geographical area and remarkable climatic diversity, is considered a highly sensitive and susceptible country in terms of heat stress in workplaces. Based on climatic classification, more than 82% of the country's area is located in arid and semi-arid regions of the world [10]. Southern provinces such as Bushehr, Khuzestan, and Hormozgan, with average summer temperatures above 45°C and relative humidity exceeding 80%, are recognized as one of the hottest and most humid regions in the world [11]. In contrast, the central and southeastern regions of the country experience hot and dry climates with intense solar radiation [12]. These harsh climatic conditions, especially during the hot seasons, expose millions of workers in various industries including oil and gas, petrochemicals, steel and foundries, open-pit mines, traditional bakeries, agricultural and construction occupations to high levels of heat stress [13-16]. In the last two decades, numerous studies in Iran have investigated the status of heat stress in various industries using the WBGT index. For example, studies in Asaluyeh have shown that the WBGT index in summer reaches above 37°C, which is significantly higher than the permissible limits (28°C for heavy work) [11, 17]. In traditional bakeries, due to direct radiant heat from ovens, heat stress has been reported above the permissible limits even in winter [18]. Furthermore, meta-analyses conducted at the global level indicate that the mean WBGT in industries has been increasing over time, and this increase has been more evident after 2010 [19].

Despite the abundance of scattered studies, the lack of a comprehensive systematic review and meta-analysis that provides a clear picture of the status of heat stress in various industries in Iran and analyzes its trend over the last two decades is a fundamental scientific gap.

Such a study can, while identifying high-risk industries and regions, provide the baseline data necessary for national decision-making, development of local standards, prioritization of control interventions, and strategic planning for adaptation to global warming. Accordingly, the present study was designed and conducted with the aim of systematically investigating the level of heat stress based on the WBGT index in various industries in Iran, analyzing the trend of mean WBGT changes during 2004-2023 (20 years), and identifying factors affecting the heterogeneity of results using a meta-regression approach.

2. Methods

2.1 Study Protocol

This study was conducted as a systematic review and meta-analysis according to the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines.

2.2 Search Strategy

A systematic search was performed in national and international databases including Web of Science, Scopus, PubMed, ScienceDirect, Iran Medex, Magiran, Google Scholar, SID, Irandoc, and Barakatkn. Search keywords included a combination of Persian and English terms using Boolean operators (AND, OR): Heat stress, Heat strain, Heat exposure, Hot condition, WBGT, WBGT index, Occupational health, Iran (in English and Persian).

The search timeframe was from January 1, 2004 to December 31, 2023 (20 years).

2.3 Inclusion and Exclusion Criteria:

2.3. Inclusion and Exclusion Criteria

Studies were eligible for inclusion if they met the following criteria:

- Cross-sectional, case-control, or interventional studies conducted in Iran;
- Heat stress assessed using the Wet Bulb Globe Temperature (WBGT) index, either through direct measurement or calculation;
- The mean and standard deviation of WBGT reported, or sufficient data provided to calculate these values;
- The target population consisted of workers employed in various industries, including indoor and outdoor workplaces; and
- Full-text articles available in either Persian or English.

Studies were excluded if they met any of the following criteria:

- Laboratory-based studies conducted in climate chambers that did not simulate actual industrial working conditions;
- Review articles, letters to the editor, or conference proceedings for which the full text was unavailable;
- Studies comparing WBGT with other heat stress indices without reporting the mean WBGT; or
- Studies involving athletes or military personnel under non-industrial conditions.

2.4 Data Extraction

2.4. Data Extraction

Two researchers independently extracted data from all eligible articles using a standardized data extraction form. Any discrepancies between the researchers were resolved through discussion and consultation with a third researcher. The following data were extracted from each study:

- **Bibliographic characteristics:** first author, year of publication, and city/province where the study was conducted;
- **Industry characteristics:** industry type and work environment (outdoor/indoor);
- **Sample characteristics:** sample size and number of WBGT measurement points;
- **WBGT measurements:** mean and standard deviation of WBGT;
- **Study characteristics:** season and year of data collection; and
- **Environmental conditions:** mean ambient temperature and relative humidity, when reported.

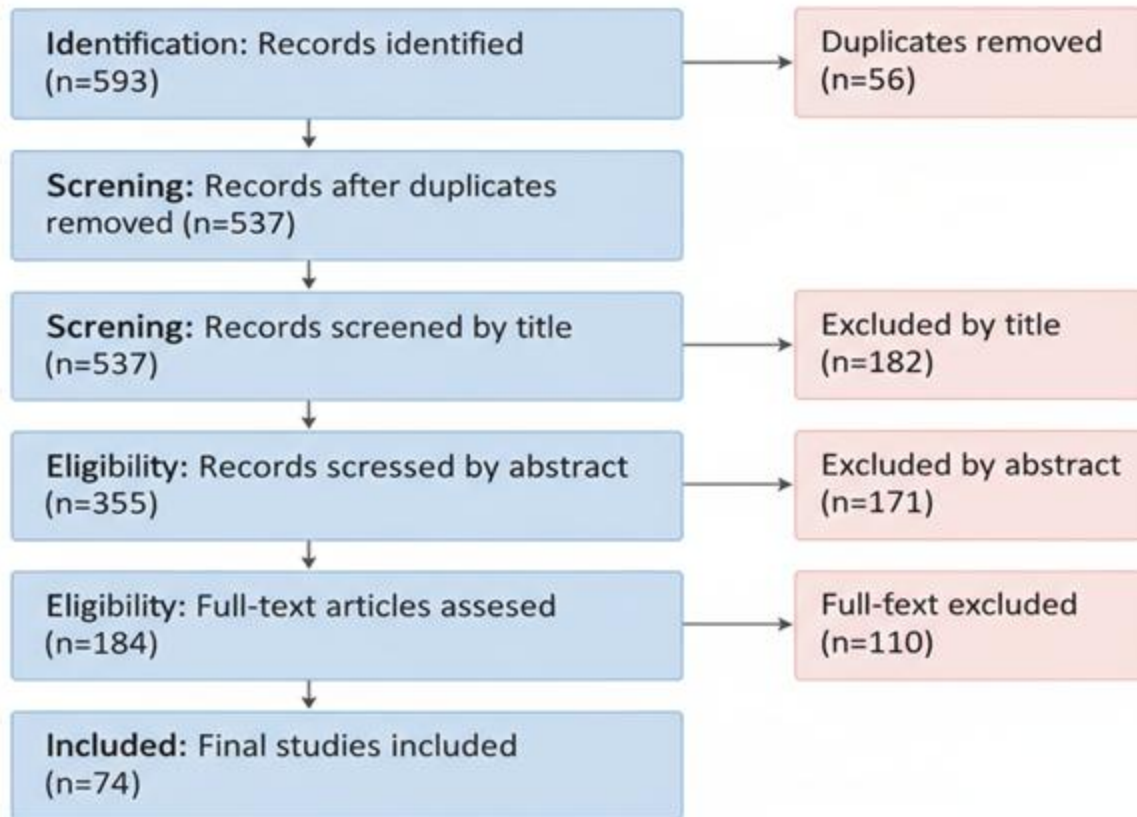


Figure 1: Summary of the article review process

2.5 Quality Assessment of Studies

The quality of included studies was assessed using the Joanna Briggs Institute (JBI) checklist for cross-sectional studies and the CASP checklist for case-control studies. Scoring was performed based on the relevant criteria, and studies with low quality were excluded from the final analysis.

2.6 Statistical Analysis

Effect Size: Mean WBGT (with 95% confidence interval) was considered as the main effect size.

Statistical Model: Due to anticipated heterogeneity between studies, a random-effects model using the inverse variance method was employed.

Heterogeneity: Heterogeneity was assessed using the I^2 statistic ($I^2 > 75\%$ indicating substantial heterogeneity).

Subgroup Analysis: To identify sources of heterogeneity, subgroup analysis was performed based on industry type (bakery, steel, oil/petrochemical, mining, agriculture), work environment type (outdoor vs. indoor), and climatic region (hot-humid south, hot-dry center, temperate north).

Temporal Trend Analysis: To investigate changes in mean WBGT over the 20-year period, meta-regression analysis was performed using the study year as a predictor variable.

Publication Bias: Publication bias was assessed using funnel plots and Egger's and Begg's statistical tests. All analyses were performed using STATA software version 17 (StataCorp, College Station, TX, USA).

3. Results

3.1 Study Selection and Screening

In the initial search, a total of 593 articles were identified. After removing duplicate articles (56 articles), 537 articles remained for screening. After reviewing titles and abstracts, 355 articles were excluded, and 184 articles were selected for full-text evaluation. In the final stage, 141 articles were excluded for various reasons (lack of reporting of mean WBGT, laboratory conditions, lack of access to full text), and finally 43 studies (including 19 studies in open environments and 24 studies in roofed environments) that met the inclusion criteria were included in the analysis.

3.2 Characteristics of Included Studies

Tables 1 present the complete characteristics of the 43 included studies. The studies were conducted between 2004 and 2023 in 15 different provinces of Iran. The diversity of industries examined included bakeries, steel and foundry industries, oil and petrochemicals, mines, agriculture, glass industries, dry cleaning, confectioneries, urban services, and hospitals.

Table 1. Characteristics of the 43 studies included in the systematic review and meta-analysis

Row	Author, Year	Year	Study Type	Participants	Measurement Points	City	Province	Industry/Occupation	Mean WBGT	Standard Deviation	95% CI	Environment
1	Abedzadeh, 2007	2007	Descriptive-analytical	9	-	Kerman	Kerman	Underground mining	12.3	0.9	11.71 - 12.89	Outdoor
2	Golbabaei, 2015	2015	Descriptive-analytical	6	6	Shabestar	East Azerbaijan	Urban services	21.0	1.42	19.86 - 22.14	Outdoor

3	GOLBABAEI, 2013	2013	Cross-sectional-descriptive	21	-	South	South	Petrochemical	21.45	0.18	21.37 - 21.53	Outdoor
4	Jalilian, 2023	2023	Cross-sectional	63	-	Qom	Qom	Sanitary urban services	21.7	0.83	21.50 - 21.90	Outdoor
5	HEIDARI, 2015	2015	Cross-sectional-descriptive	24	48	North	North	Livestock farming	22.6	5.49	22.31 - 22.89	Outdoor
6	GOLBABAEI, 2014	2014	Comparative-experimental	6	-	Tehran	Tehran	Construction	22.6	0.36	25.90 - 29.10	Outdoor
7	Rashidi, 2018	2018	Cross-sectional-descriptive	97	-	Qom	Qom	Green space/landscaping	25.57	1.68	25.24 - 25.90	Outdoor
8	HEIDARI, 2015	2015	Cross-sectional-descriptive	30	60	North	North	Agriculture	25.64	2.41	24.78 - 26.50	Outdoor
9	biyabani, 2021	2021	Descriptive-analytical	154	-	Asaluyeh	Bushehr	Oil terminal	26.27	3.01	25.79 - 26.75	Outdoor
10	Golbabaei, 2015	2015	Cross-sectional-descriptive	5	5	Shabestar	East Azerbaijan	Concrete production	26.32	1.29	25.19 - 27.45	Outdoor
11	Golbabaei, 2015	2015	Cross-sectional-descriptive	5	5	Shabestar	East Azerbaijan	Green space/landscaping	26.38	2.27	24.39 - 28.37	Outdoor
12	Golbabaei, 2015	2015	Cross-sectional-descriptive	4	4	Shabestar	East Azerbaijan	Cargo handling	26.68	2.0	24.72 - 28.64	Outdoor
13	HEIDARI, 2015	2015	Cross-sectional-descriptive	25	50	North	North	باغدارى	26.8	3.51	25.42 - 28.18	Outdoor
14	RAHIMI FARD, 2021	2021	Descriptive-analytical	330	-	Rasht	Gilan	Vendor	27.4	1.85	27.20 - 27.60	Outdoor
15	GOLBABAEI, 2014	2014	Comparative-experimental	6	-	Tehran	Tehran	Construction	27.5	0.48	27.12 - 27.88	Outdoor
16	Zamanian, 2017	2017	Descriptive-analytical	387	-	Bukan	West Azerbaijan	Farmers	27.65	0.93	27.56 - 27.74	Outdoor
17	Falahati, 2012 / ALIMOHAMADI, 2012	2012	Descriptive-analytical	94	11	Khark	Bushehr	Oil terminal	29.76	3.51	29.05 - 30.47	Outdoor
18	mohammadianm, 2019	2019	Descriptive-analytical	59	-	Jiroft	Kerman	Date workers	33.2	1.84	32.73 - 33.67	Outdoor
19	Dehghan, 2018	2018	Cross-sectional	90	-	Asaluyeh	Bushehr	-	37.65	2.1	37.22 - 38.08	Outdoor
20	Abedzadeh, 2007	2007	Descriptive-analytical	9	-	Kerman	Kerman	Underground mining	14.3	0.89	13.72 - 14.88	Indoor
21	ALINAGHI LANGARI, 2020	2020	Cross-sectional	30	-	Kerman	Kerman	Office employees	17.2	0.5	17.02 - 17.38	Indoor

22	Haji Azimi, 2017	2017	Analytical cross-sectional	64	-	Tehran	Tehran	Underground mining	22.08	1.14	21.80 - 22.36	Indoor
23	Mobasheri-Demneh, 2018	2018	Cross-sectional	64	-	Isfahan	Isfahan	Underground mining	22.08	1.41	21.73 - 22.43	Indoor
24	akhlaghi, 2019	2019	Case-control	35	-	Tehran	Tehran	Foundry	24.2	5.1	22.51 - 25.89	Indoor
25	ALINAGHI LANGARI, 2020	2020	Cross-sectional	30	-	Kerman	Kerman	Refinery workers	25.3	0.8	25.01 - 25.59	Indoor
26	mohebyan, 2019	2019	Descriptive-analytical	118	-	Iranshahr	Sistan and Baluchestan	Hospital	25.9	0.83	25.75 - 26.05	Indoor
27	Falahati, 2012	2012	Descriptive-analytical	94	11	South	South	Oil terminal	26.19	4.56	25.27 - 27.11	Indoor
28	GHOTBI RAVANDI, 2016	2016	Cross-sectional	54	-	Kerman	Kerman	Metal smelting	27.3	2.9	26.53 - 28.07	Indoor
29	GOLBABAEI, 2014	2014	Comparative-experimental	6	-	Tehran	Tehran	Construction	27.5	0.48	27.12 - 27.88	Indoor
30	Jalali, 2017	2017	Cross-sectional	40	-	Tehran	Tehran	Foundry	27.59	3.4	26.54 - 28.64	Indoor
31	Rezaei, 2018	2018	Descriptive-analytical	220	-	Tehran	Tehran	Steel company	28.28	2.06	28.01 - 28.55	Indoor
32	Malakoti, 2015	2015	Descriptive-analytical	113	-	Qom	Qom	Laundry	28.98	1.64	28.68 - 29.28	Indoor
33	Gharibi, 2020	2020	Cross-sectional	163	-	Shahrud	Semnan	Bakery	29.35	2.1	29.03 - 29.67	Indoor
34	HOORFARASAT, 2015	2015	Cross-sectional	72	-	Tehran	Tehran	Glass factory	30.2	1.06	29.96 - 30.44	Indoor
35	Dehghan, 2012	2012	Cross-sectional-descriptive	51	-	Isfahan	Isfahan	Steel company	30.8	4.4	29.59 - 32.01	Indoor
36	afshari, 2021	2021	Descriptive-analytical	60	-	Ahvaz	Khuzestan	Steel company	30.86	1.2	30.56 - 31.16	Indoor
37	Rashidi, 2020	2020	Descriptive-analytical	104	-	Ilam	Ilam	Confectionery	31.53	3.8	30.80 - 32.26	Indoor
38	MONAZZAM, 2014	2014	Cross-sectional-descriptive	10	-	South	South	Petrochemical	32.08	0.08	32.03 - 32.13	Indoor
39	Hanani, 2004	2004	Descriptive-analytical	175	175	Hamedan	Hamedan	Bakery	32.6	2.4	32.24 - 32.96	Indoor
40	GOLBABAEI, 2013	2013	Cross-sectional-descriptive	21	-	South	South	Petrochemical	32.98	0.86	32.61 - 33.35	Indoor
41	Dehghan, 2012	2012	Cross-sectional-descriptive	71	-	Asaluyeh	Bushehr	Steel company	33.3	0.2	33.25 - 33.35	Indoor
42	akhlaghi, 2019	2019	Case-control	25	-	Tehran	Tehran	Foundry	33.8	3.4	32.47 - 35.13	Indoor
43	Mahdavia, 2014	2014	Descriptive	41	-	Lorestan	Lorestan	Steel company	40.2	2.135	39.55 - 40.85	Indoor

3.3 Meta-Analysis Results: Open Environment

Meta-analysis for the open environment was performed using 19 studies. The random-effects model estimated the mean WBGT at 25.71°C (95% CI: 23.36–28.06), which was statistically significant ($p < 0.0001$). The range of WBGT in different studies varied from 12.30°C (underground mine, Abedzadeh, 2007) to 37.65°C (Dehghan, 2018). Very high heterogeneity was observed between studies ($I^2 = 99.93\%$, Q-test $p < 0.0001$), indicating the wide diversity of environmental conditions and the need for subgroup analyses.

3.4 Meta-Analysis Results: Roofed Environment

Meta-analysis for the roofed environment was performed using 24 studies. The random-effects model estimated the mean WBGT at 28.11°C (95% CI: 25.88–30.34), which was statistically significant ($p < 0.0001$). The range of WBGT in different studies varied from 14.30°C (underground mine, Abedzadeh, 2007) to 40.20°C (steel industry, Mahdavia, 2014). Very high heterogeneity was also observed in this environment ($I^2 = 99.97\%$, Q-test $p < 0.0001$).

3.5 Subgroup Analyses

Open Environment - Industry: Subgroup analysis based on industry type showed significant differences between various industries. The highest mean WBGT was related to date harvesting workers (33.20°C) and the lowest to underground mines (12.30°C). The moderator effect of industry was significant (QM = 110.42, $p < 0.0001$) and explained 85.66% of the heterogeneity.

Open Environment - Province: Subgroup analysis based on province showed no significant difference between different provinces (QM = 3.51, $p = 0.9407$), and province did not play an important role in the heterogeneity of open environment studies ($R^2 = 0.00\%$).

Open Environment - Year: Studies conducted after 2010 had a higher mean WBGT (26.47°C) compared to studies before 2010 (26.63°C), which was consistent with the meta-regression results (coefficient = 0.68, $p = 0.0248$).

Roofed Environment - Industry: Significant differences were observed between different industries, with the steel industry at 40.20°C and underground mines at 14.30°C having the highest and lowest values, respectively. The moderator effect of industry was significant (QM = 29.92, $p = 0.0078$) and explained 41.12% of the heterogeneity.

Roofed Environment - Province: Subgroup analysis based on province showed significant differences between different provinces (QM = 23.32, $p = 0.0251$), and province explained 33.17% of the heterogeneity.

Roofed Environment - Year: Unlike the open environment, no significant increasing trend was observed over time ($p = 0.3392$), indicating relative stability of thermal conditions in roofed environments.

3.6 Meta-Regression

Meta-regression results showed that in open environments, the study year had a significant relationship with mean WBGT (coefficient = 0.68, $p = 0.0248$, $R^2 = 18.39\%$), such that for each year, the mean WBGT increased by approximately 0.68°C. In roofed environments, this relationship was not significant (coefficient = -0.0054, $p = 0.3392$, $R^2 = 0.00\%$).

3.7 Publication Bias

The funnel plot for roofed environments was approximately symmetrical, and Egger's test showed no significant publication bias ($p = 0.142$). For open environments, the funnel plot was slightly asymmetrical, suggesting the possibility of publication bias or small-study effects. Sensitivity analysis by removing studies one by one showed that the overall results of the meta-analysis in both environments were stable, and no single study had a significant impact on the final estimate.

Overall Random-Effects Models

Open Environment

The random-effects meta-analysis for the open environment, encompassing 19 studies, produced a pooled mean Wet Bulb Globe Temperature (WBGT) of 25.71°C (95% CI: 23.36, 28.06; $p < 0.0001$), as illustrated in the forest plot (Figure 1). This plot reveals considerable variability in mean WBGT values, ranging from 12.30°C (Abedzadeh 2007 Underground Mine, 95% CI: 11.71, 12.89) to 37.65°C (Dehghan 2018 NA, 95% CI: 37.22, 38.08). Confidence intervals (CIs) vary in width, with narrower intervals indicating higher precision (e.g., Jalilian 2023: 21.70°C, 95% CI: 21.50, 21.90) and wider intervals suggesting greater uncertainty (e.g., HEIDARI 2015 Husbandry: 22.60°C, 95% CI: 20.40, 24.80). The extreme heterogeneity ($I^2 > 99.9\%$, Q-test $p < 0.0001$) highlights diverse environmental conditions across occupational settings and geographical locations, necessitating subgroup analyses to elucidate sources of variation.

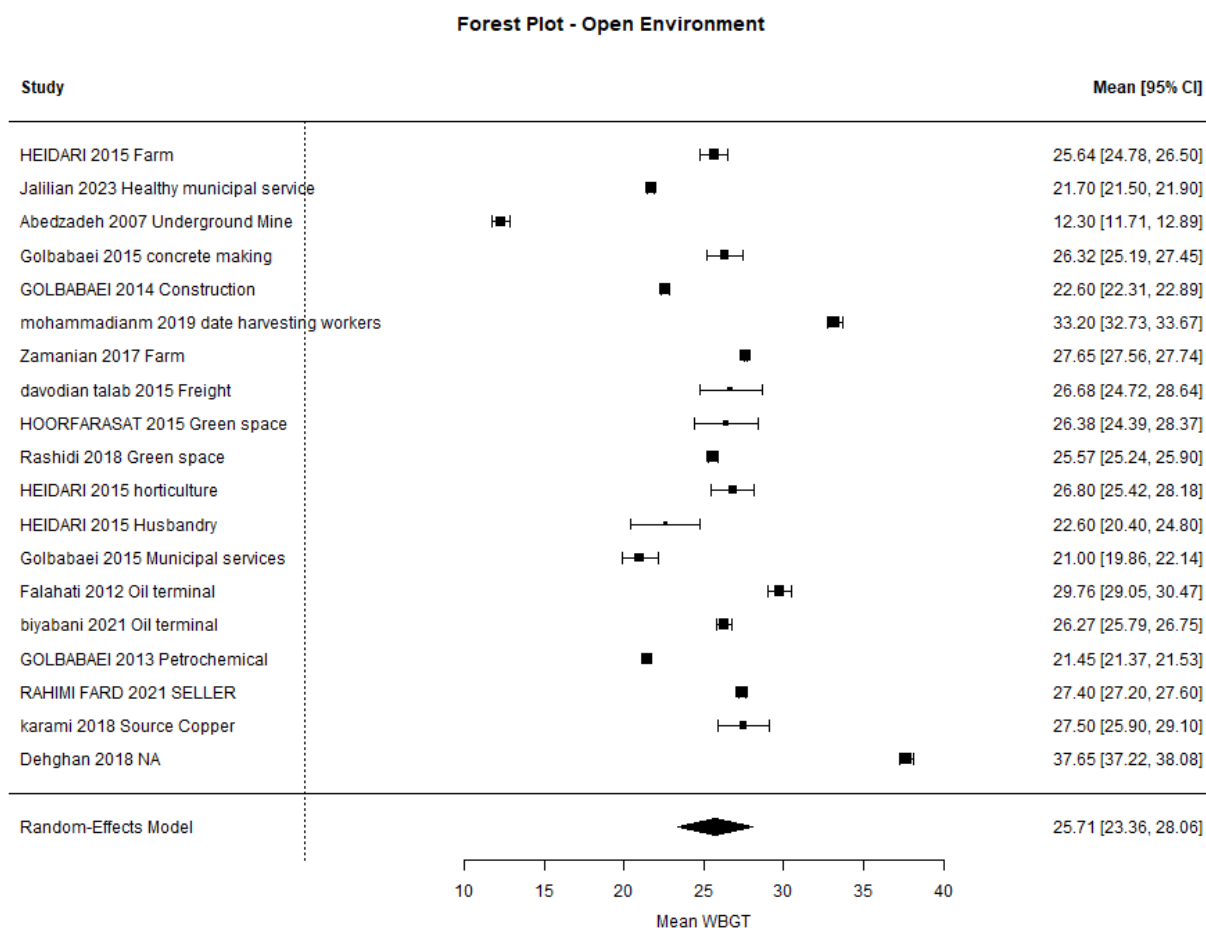
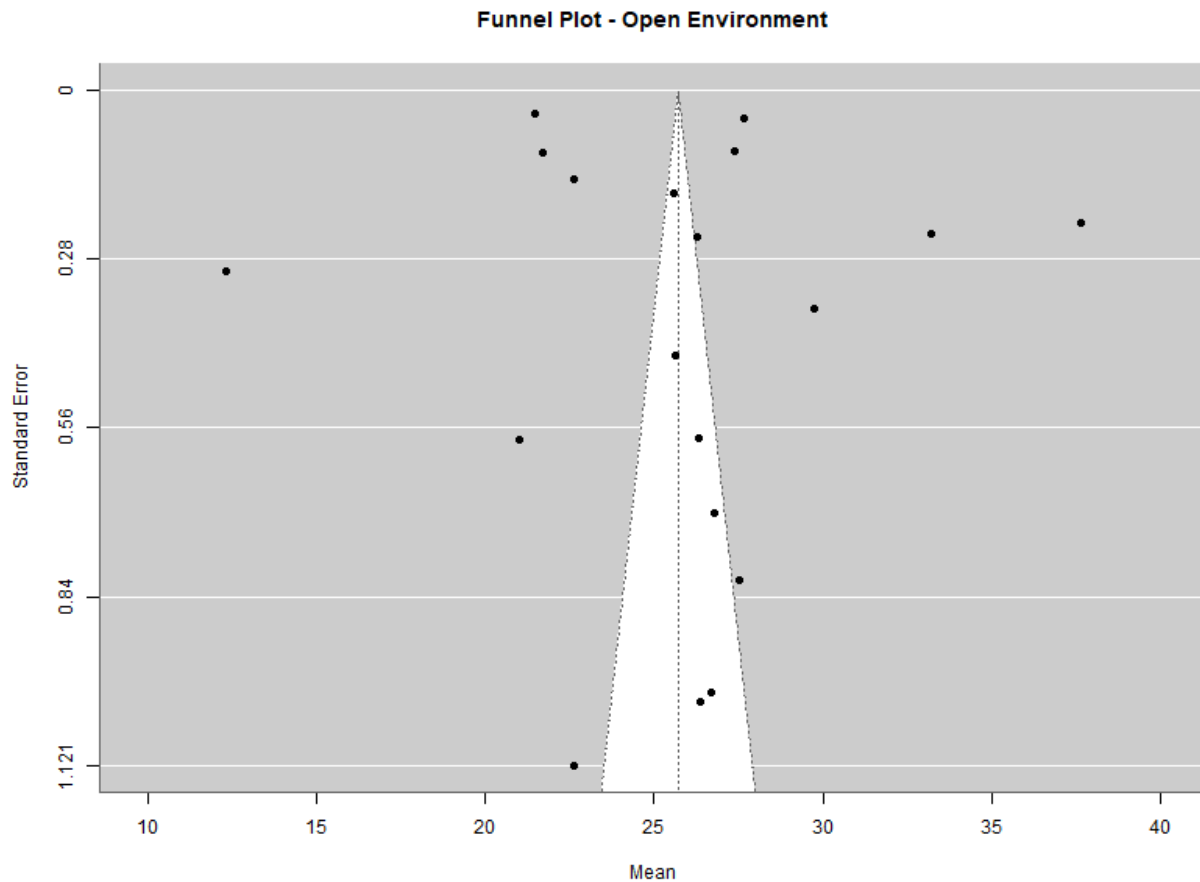


Figure 1. Forest plot of the pooled mean Wet Bulb Globe Temperature (WBGT) in open environments



Roofed Environment

For the roofed environment, comprising 24 studies, the random-effects model yielded a pooled mean WBGT of 28.11°C (95% CI: 25.88, 30.34; $p < 0.0001$), as depicted in the forest plot (Figure 2). Individual study means span from 14.30°C (Abedzadeh 2007 Underground Mine, 95% CI: 13.72, 14.88) to 40.20°C (Mahdavia 2014 Steel Company, 95% CI: 39.55, 40.85). The CIs reflect varying precision, with studies like ALINAQHI-LANGARI 2020 employees of the administrative (17.20°C, 95% CI: 17.02, 17.38) showing tight intervals, and others like Akhlaghi 2019 Casting (24.20°C, 95% CI: 22.51, 25.89) exhibiting broader ranges. Similar to the open environment, significant heterogeneity ($I^2 > 99.9\%$, Q-test $p < 0.0001$) was observed, suggesting that factors such as industrial settings or controlled indoor conditions contribute to the variability.

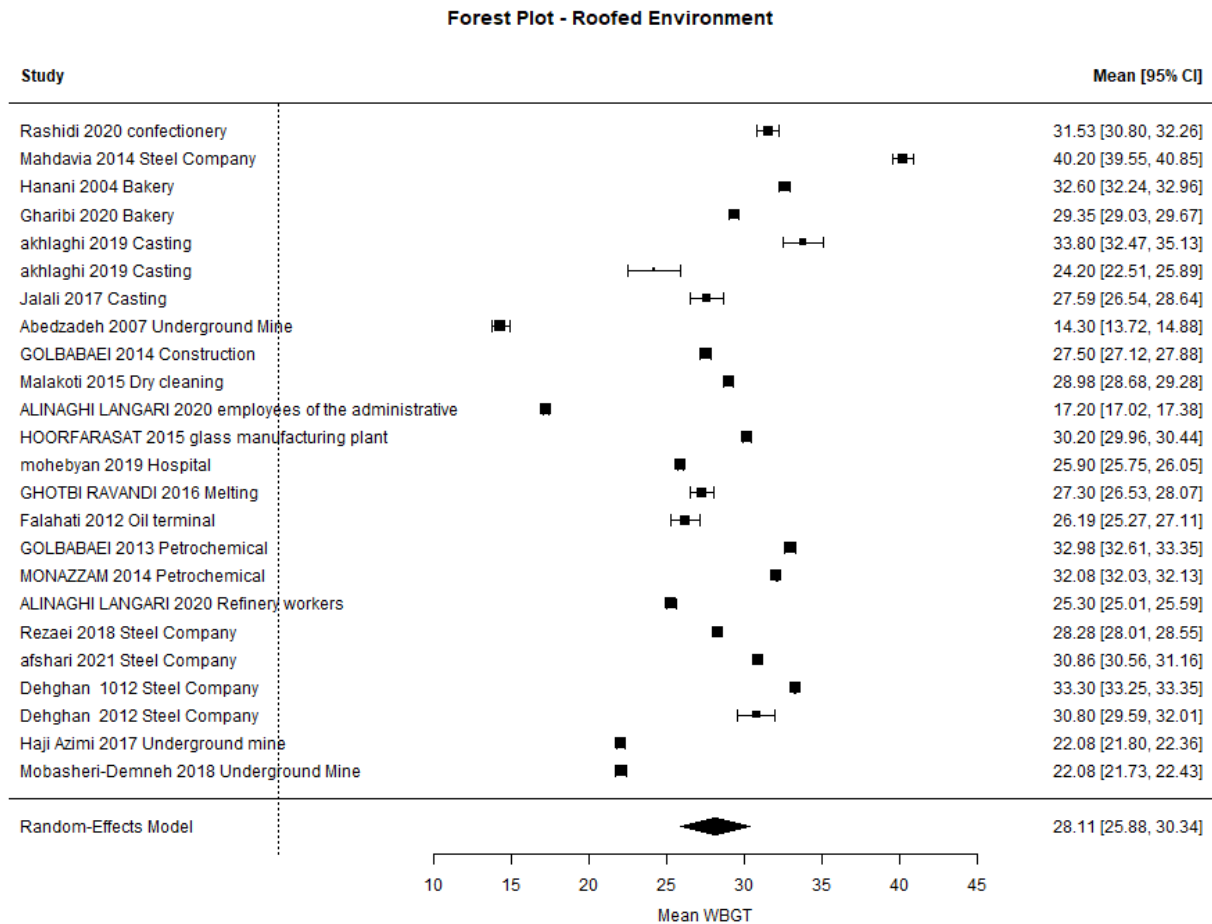
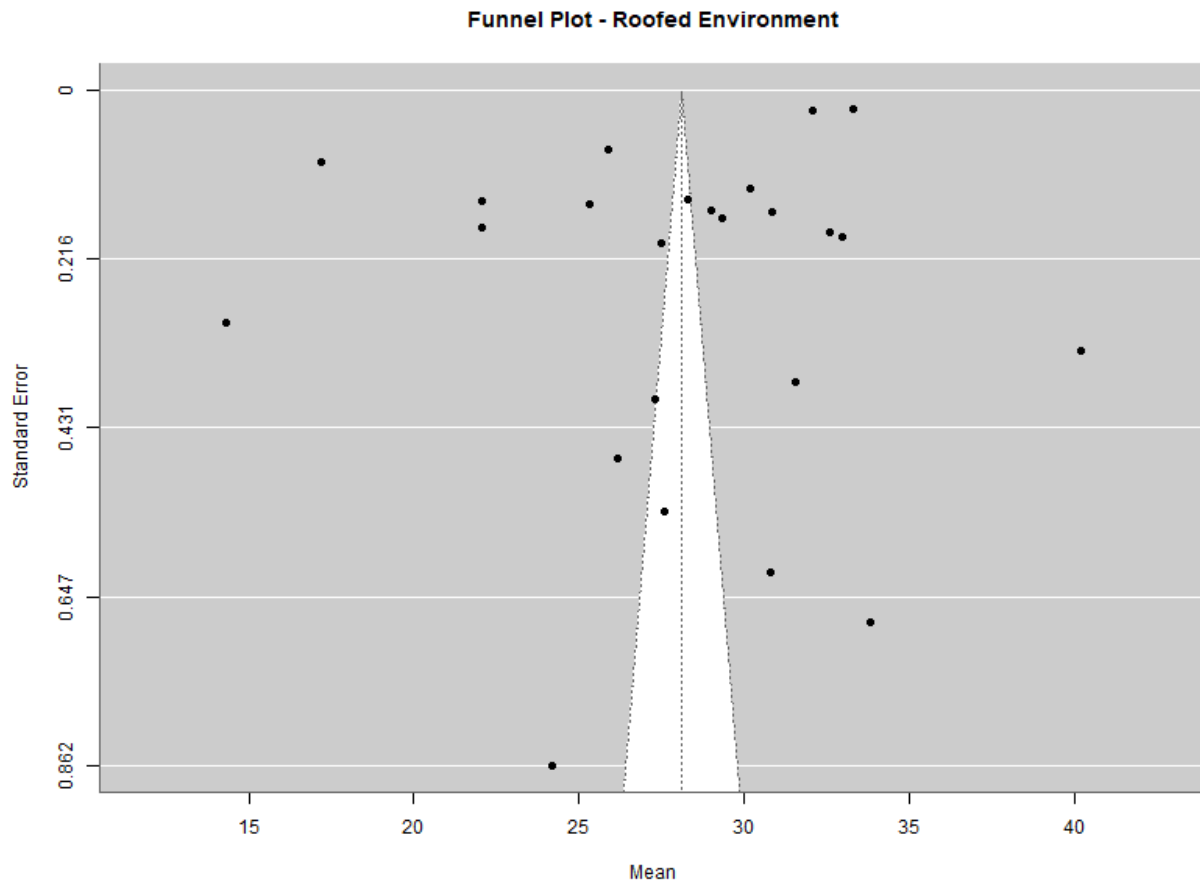


Figure 2. Forest plot of the pooled mean Wet Bulb Globe Temperature (WBGT) in roofed environments



Subgroup Analyses

Open Environment

Industry: The forest plot by industry (Figure 3) demonstrates substantial differences in WBGT across occupational sectors. For example, "date harvesting workers" (mohammadiann 2019) recorded a high mean WBGT of 33.20°C (95% CI: 32.73, 33.67), while "Underground Mine" (Abedzadeh 2007) showed a low mean of 12.30°C (95% CI: 11.71, 12.89). This variability corresponds to a significant moderator effect (QM=110.42, $p<0.0001$), explaining 85.66% of the heterogeneity ($R^2=85.66\%$), underscoring the influence of industry-specific conditions on thermal stress.

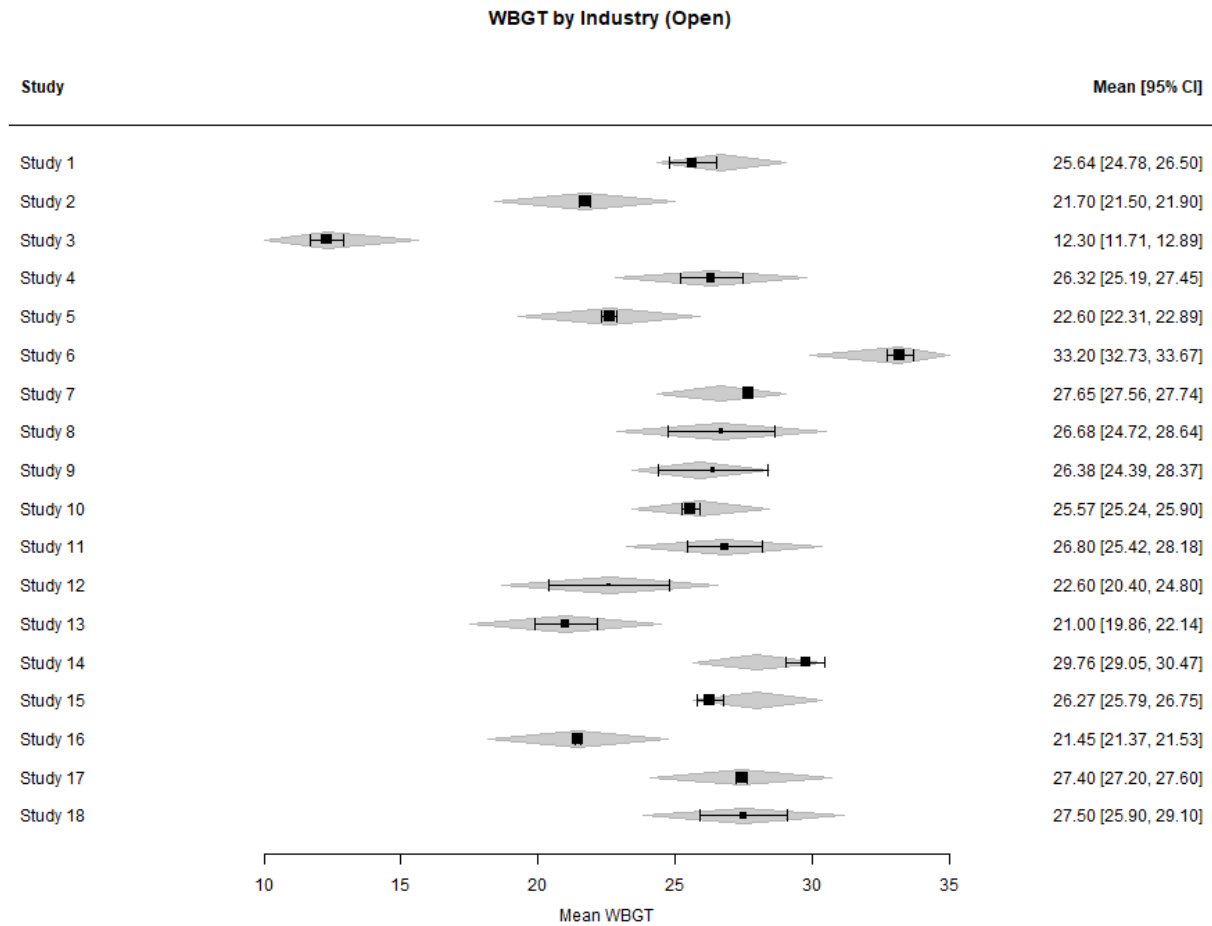


Figure 3. Forest plot of pooled mean Wet Bulb Globe Temperature (WBGT) by industry type in open environments

Province: The forest by province (Figure 4) illustrates diverse WBGT distributions across regions, with means ranging from 12.30°C (Study 3) to 37.65°C (Study 19). However, the subgroup analysis indicated no significant moderator effect ($QM=3.51$, $p=0.9407$), suggesting that province is not a primary contributor to heterogeneity in open environments.

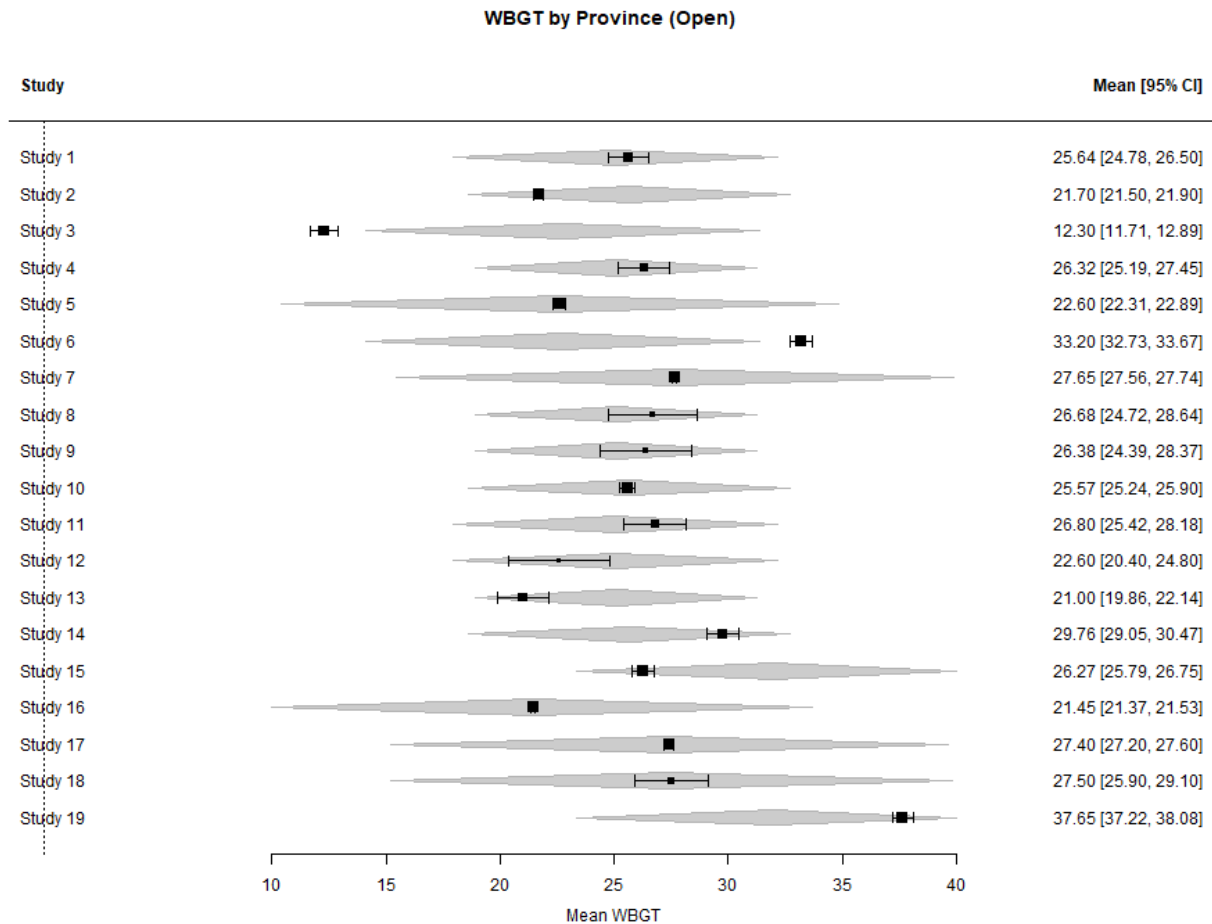


Figure 4. Forest plot of pooled mean Wet Bulb Globe Temperature (WBGT) by province in open environments

Year Group: The forest plot by year group (Figure 5) reveals temporal differences, with "2010 and after" studies averaging higher WBGT (e.g., 26.47°C) compared to "Before 2010" (e.g., 12.30°C, Abedzadeh 2007). This aligns with a significant year effect in meta-regression (coefficient=0.68, $p=0.0248$), indicating a trend of increasing thermal stress over time.

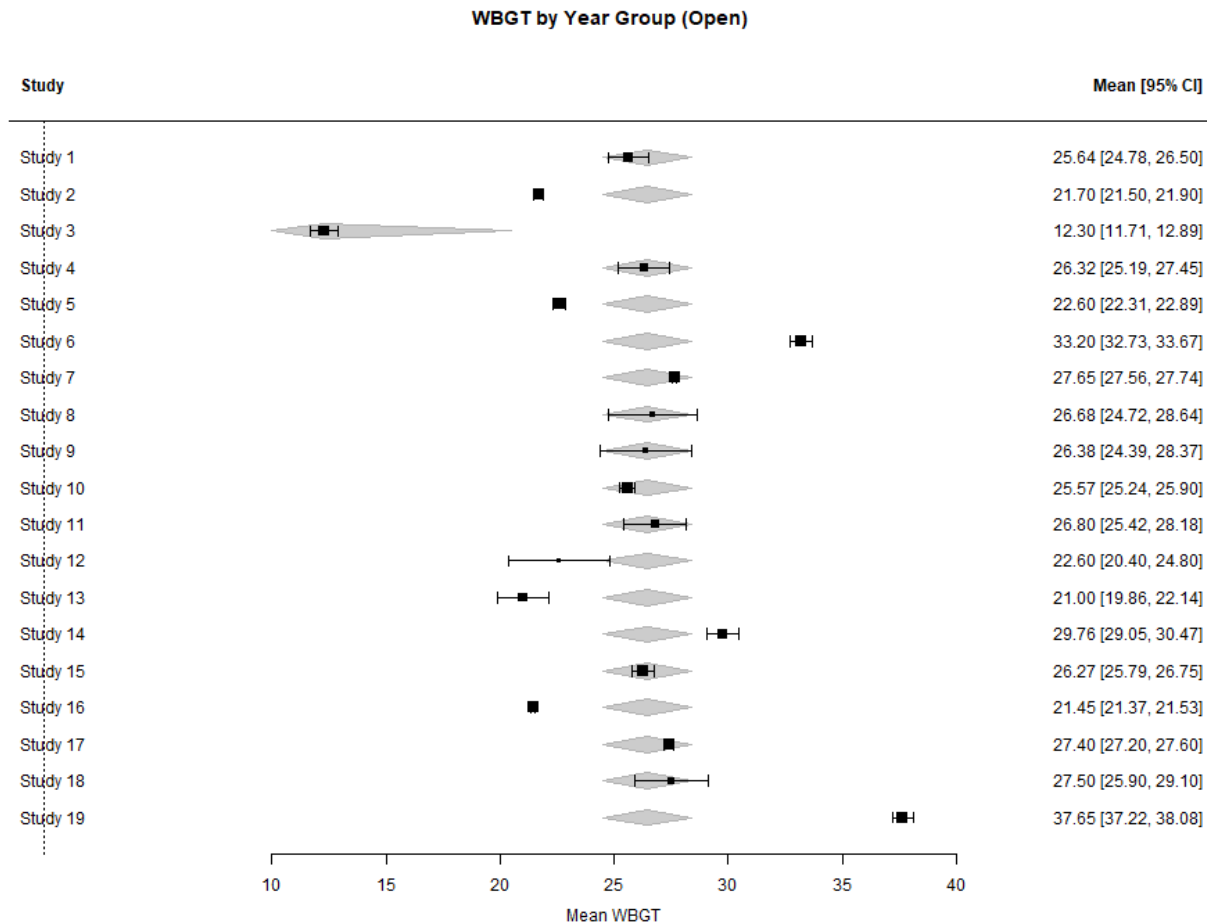


Figure 5. Forest plot of pooled mean Wet Bulb Globe Temperature (WBGT) by study year group in open environments

Roofed Environment

Industry: The forest plot by industry (Figure 6) highlights significant variability, with "Steel Company" studies reporting elevated WBGT (e.g., Mahdavia 2014: 40.20°C, 95% CI: 39.55, 40.85) and "Underground Mine" showing lower values (e.g., Abedzadeh 2007: 14.30°C, 95% CI: 13.72, 14.88). The significant moderator effect ($QM=29.92$, $p=0.0078$) accounts for 41.12% of the heterogeneity, reflecting the impact of industrial processes on indoor thermal conditions.

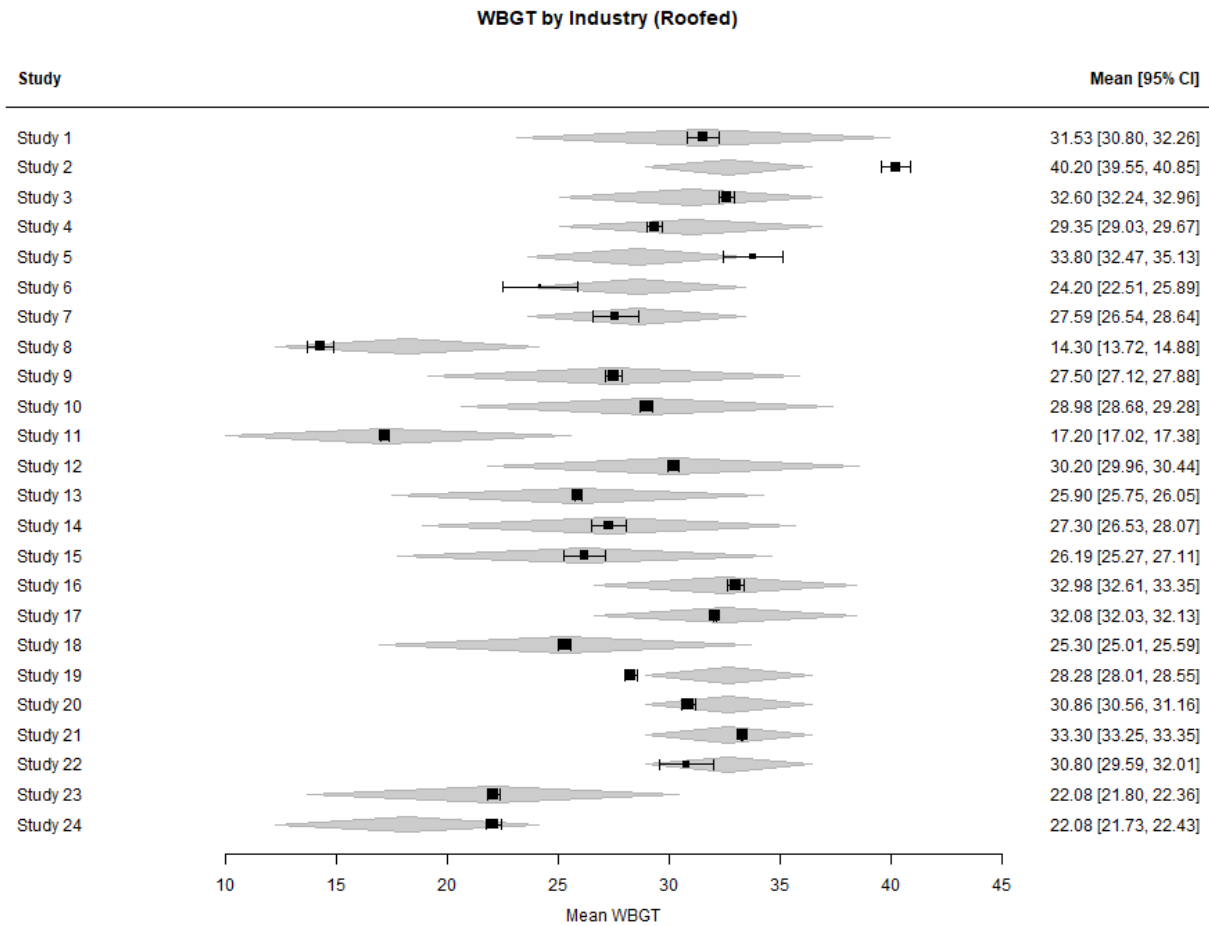


Figure 6. Forest plot of mean Wet Bulb Globe Temperature (WBGT) by industry type in roofed environments

Province: The forest plot by province (Figure 7) shows regional differences, with some provinces exhibiting higher WBGT (e.g., Study 2: 40.20°C, 95% CI: 39.55, 40.85) and others lower (e.g., Study 11: 17.20°C, 95% CI: 17.02, 17.38). This variability corresponds to a significant moderator effect (QM=23.32, $p=0.0251$), suggesting provincial influences on WBGT in roofed settings.

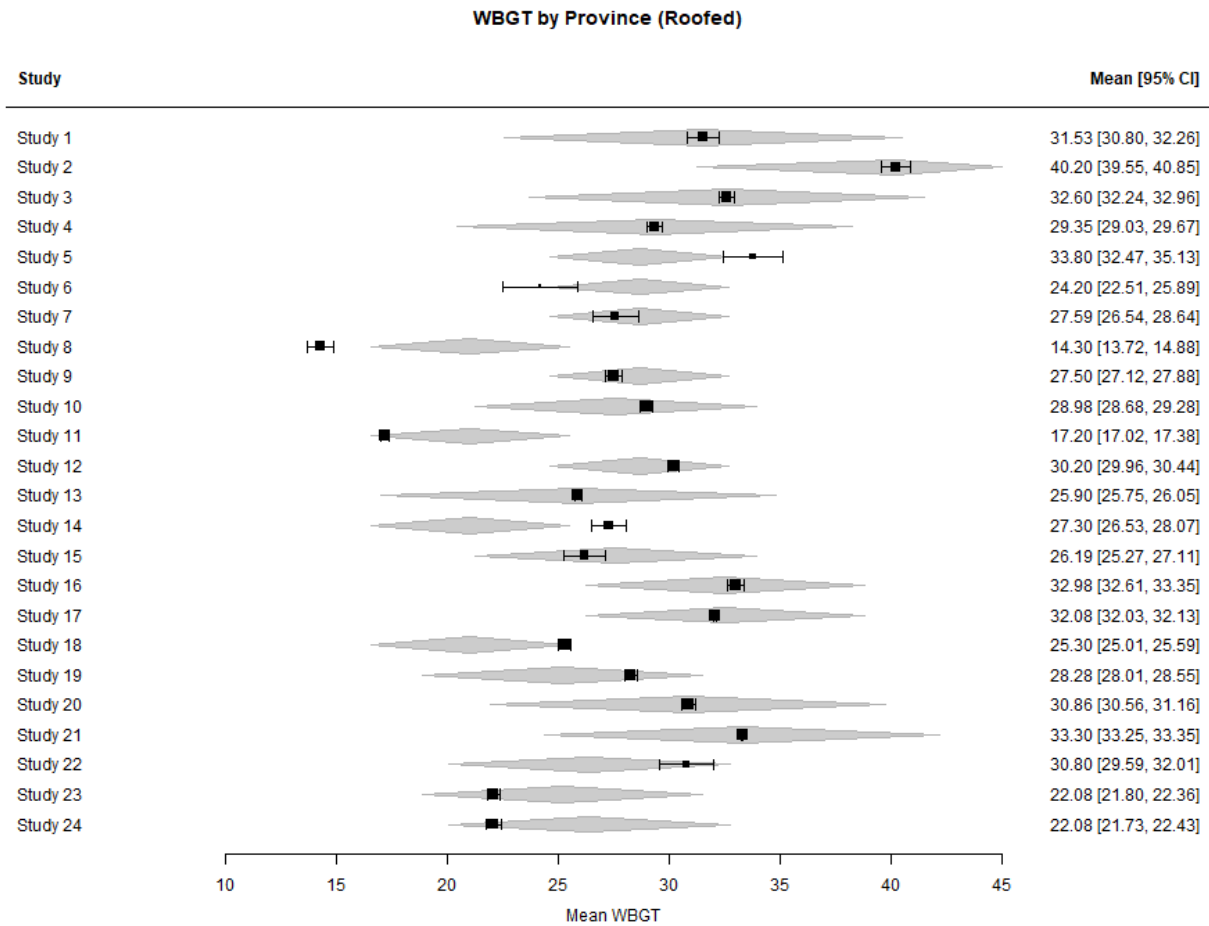


Figure 7. Forest plot of mean Wet Bulb Globe Temperature (WBGT) by province in roofed environments

Year Group: The forest by year group (Figure 8) displays overlapping WBGT distributions across studies, with means ranging from 14.30°C (Study 8) to 40.20°C (Study 2). The non-significant year effect in meta-regression ($p=0.3392$) indicates stable thermal conditions over time in roofed environments.

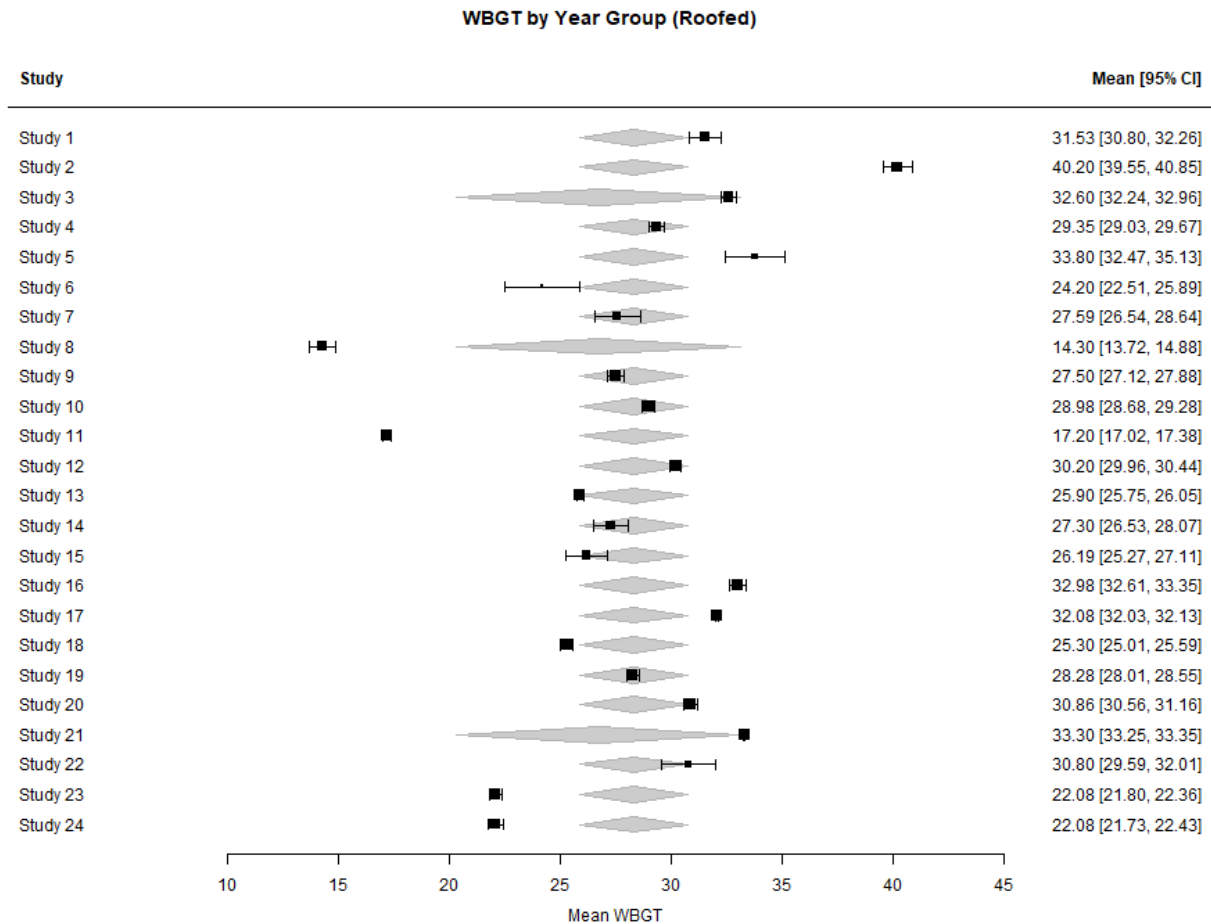


Figure 8. Forest plot of mean Wet Bulb Globe Temperature (WBGT) by study year group in roofed environments

Publication Bias Assessment

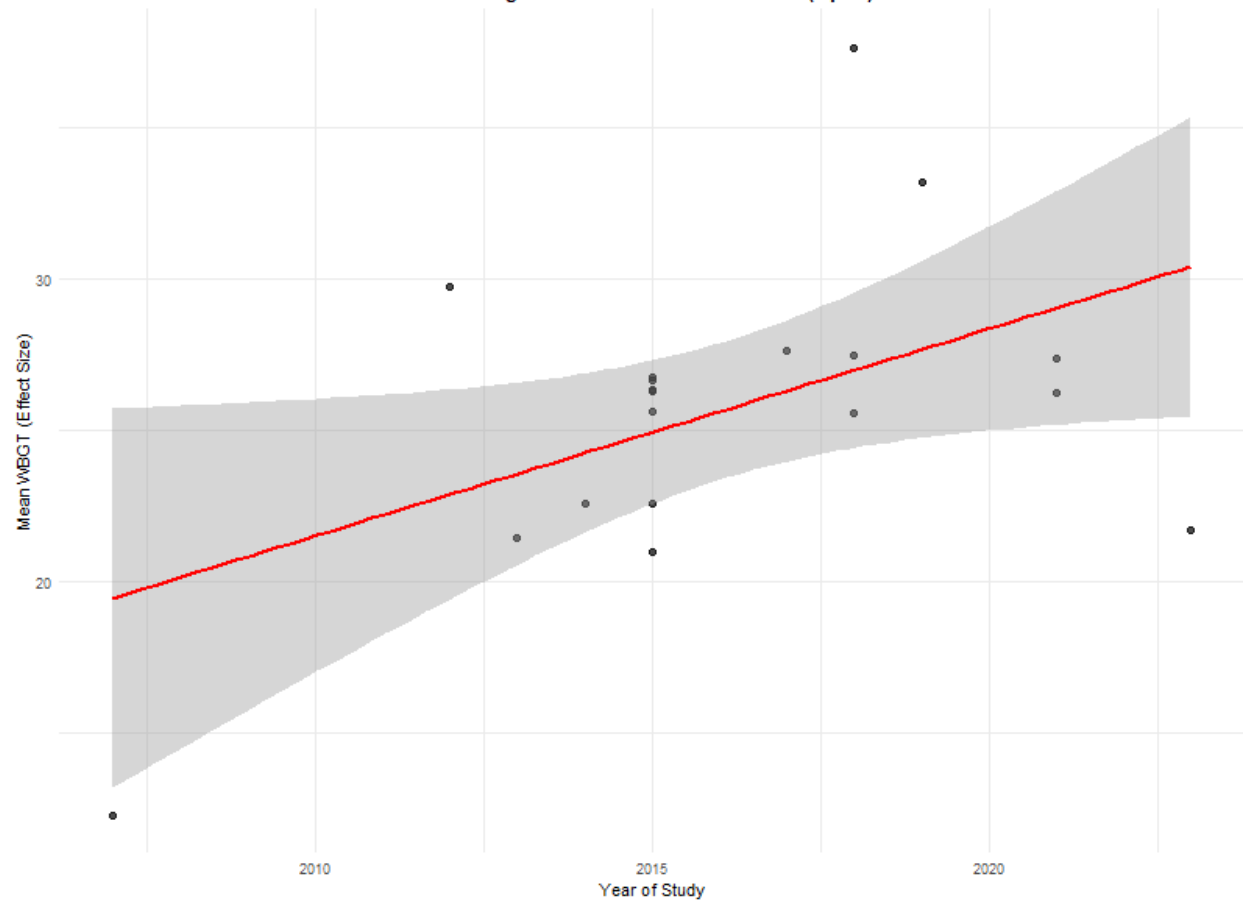
Funnel plots were employed to evaluate publication bias. For the open environment (Figure 9), the plot displays some asymmetry, with points extending beyond the funnel on the right side (e.g., an outlier at approximately 35°C, SE=0.28), suggesting potential publication bias or small-study effects. This asymmetry indicates that studies with higher WBGT means may be overrepresented, necessitating statistical confirmation (e.g., Egger's test) and sensitivity analyses. Conversely, the funnel plot for the roofed environment (Figure 10) exhibits a roughly symmetrical distribution, with most points within the funnel (centered at ~27.5°C), implying minimal publication bias. However, a few outliers at higher standard errors (e.g., SE>0.190) suggest heterogeneity rather than bias, warranting further exploration.

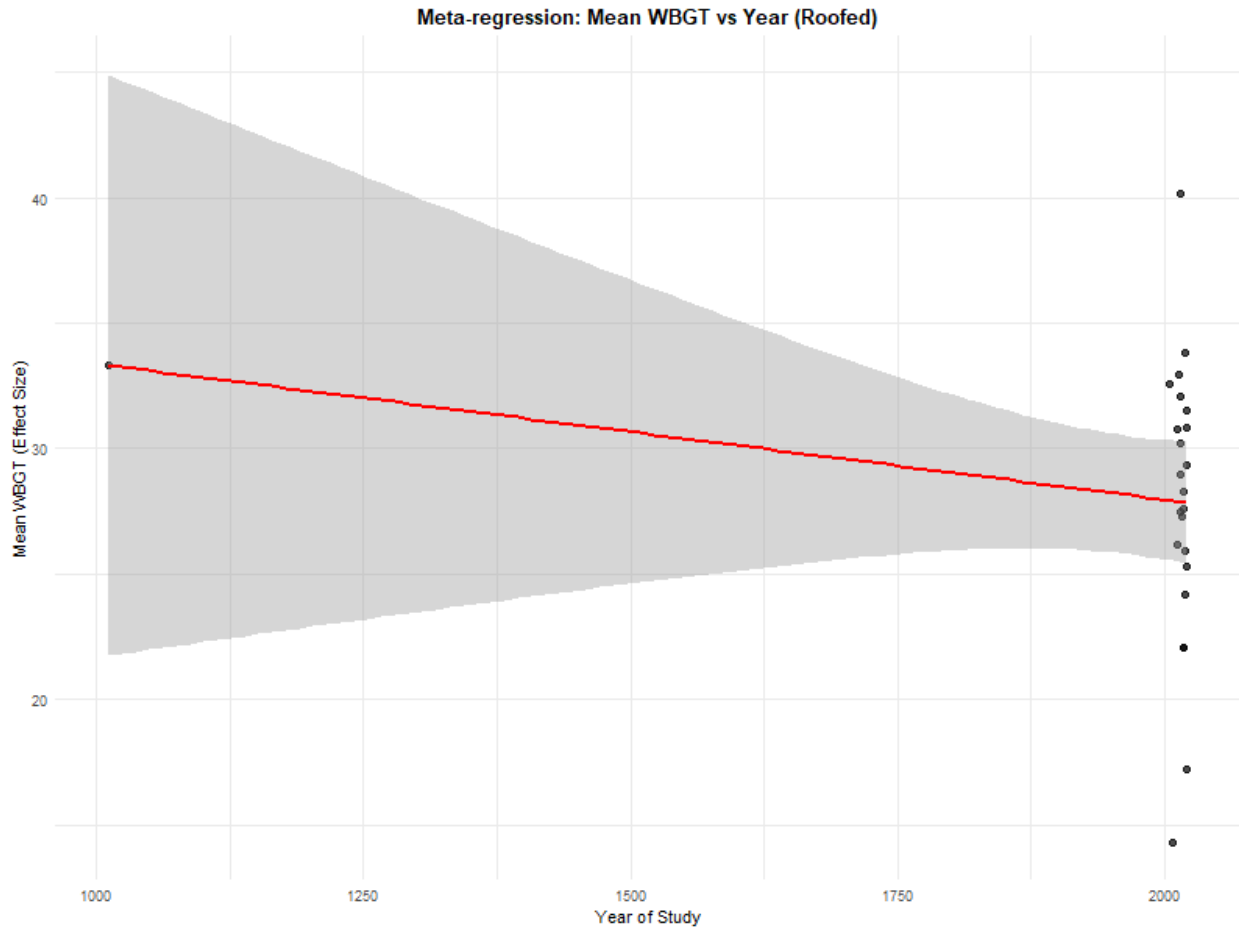
Meta-Regression

Meta-regression analyses identified a significant temporal trend in the open environment, with a coefficient of 0.68 (p=0.0248), indicating rising WBGT over time, possibly due to climate change

or increased occupational exposure. In the roofed environment, the year effect was non-significant ($p=0.3392$), suggesting that indoor thermal conditions have remained relatively consistent across the study period, likely due to controlled environments mitigating external climatic influences.

Meta-regression: Mean WBGT vs Year (Open)





Compare Open vs. Roofed Results:

Compare overall effect sizes, heterogeneity, and subgroup differences.

Highlight significant moderators (e.g., Province and Industry in Roofed, Industry and Year in Open).

Discuss implications of differences in k (19 vs. 24 studies) and heterogeneity accounted for (R^2).

Random-Effects Models

Open Meta Result ($k=19$):

Effect Size: The pooled effect size is 25.7120 (95% CI: 23.3645, 28.0595), highly significant ($p < 0.0001$, $z = 21.4675$).

Heterogeneity: $\tau^2 = 26.9580$ (SE = 9.0846), $I^2 = 99.93\%$, $H^2 = 1519.03$, $Q = 19022.6056$ ($p < 0.0001$). This indicates extreme heterogeneity, with 99.93% of variability due to between-study differences rather than sampling error.

Model Fit: AIC = 114.4521, BIC = 116.2328, AICc = 115.2521, suggesting a reasonable fit but high heterogeneity complicates interpretation.

Roofed Meta Result ($k=24$):

Effect Size: Pooled effect size is 28.1074 (95% CI: 25.8770, 30.3379), also highly significant ($p < 0.0001$, $z = 24.6988$).

Heterogeneity: $\tau^2 = 30.9621$ (SE=9.1653), $I^2 = 99.97\%$, $H^2 = 3711.06$, $Q = 51228.3780$ ($p < 0.0001$).

Heterogeneity is even higher than in Open, likely due to more studies or diverse conditions.

Model Fit: AIC=148.2966, BIC=150.5675, AICc=148.8966, indicating a slightly worse fit compared to Open, possibly due to increased complexity.

Subgroup Analyses

Roofed Province Subgroup:

Moderators: Significant (QM=23.3184, $p = 0.0251$), suggesting province explains some heterogeneity ($R^2 = 33.17\%$).

Key Finding: Kerman has a significant negative effect (-12.2803, $p = 0.0158$), lowering the effect size relative to the intercept (33.3000).

Heterogeneity: Residual $\tau^2 = 20.6918$, $I^2 = 99.80\%$, indicating substantial unexplained variability.

Roofed Industry Subgroup:

Moderators: Highly significant (QM=29.9247, $p = 0.0078$), with $R^2 = 41.12\%$.

Key Findings: Significant negative effects for “employees of the administrative” (-13.7747, $p = 0.0085$) and “Underground Mine” (-12.7787, $p = 0.0028$).

Heterogeneity: $\tau^2 = 18.2307$, $I^2 = 99.84\%$, still high but reduced compared to the overall model.

Roofed Year Subgroup:

Moderators: Not significant (QM=0.9135, $p = 0.3392$), $R^2 = 0.00\%$.

Finding: Year does not explain heterogeneity, with a negligible effect (-0.0054, $p = 0.3392$).

Open Province Subgroup:

Moderators: Not significant (QM=3.5074, $p = 0.9407$), $R^2 = 0.00\%$.

Finding: No province significantly differs from the intercept (31.9607).

Open Province Subgroup Meta Result

Open Industry Subgroup:

Moderators: Highly significant (QM=110.4219, $p < 0.0001$), $R^2 = 85.66\%$.

Key Findings: “date harvesting workers” (6.8800, $p = 0.0051$) increases effect size, while “Underground Mine” (-14.0200, $p < 0.0001$) and “Municipal services” (-5.3200, $p = 0.0341$) decrease it.

Heterogeneity: $\tau^2 = 2.8169$, $I^2 = 95.51\%$, much lower than other analyses, suggesting industry explains substantial variability.

Meta-Regression

Open (Year):

Year is significant (0.6842, $p=0.0248$), with $R^2=18.39\%$, indicating a temporal trend in effect sizes.

Intercept=-1353.6711 suggests a baseline effect far in the past, but the positive year coefficient implies increasing effects over time.

Roofed (Year):

Year is not significant (-0.0054, $p=0.3392$), $R^2=0.00\%$, suggesting no temporal trend.

The discrepancy with the document's "Meta Regression for Roofed" (which incorrectly mirrors Open's results) is resolved by using the meta_roofed_yearreg output ($p=0.3392$).

Comparison: Open vs. Roofed

Effect Size: Roofed (28.1074) is slightly higher than Open (25.7120), with overlapping CIs, suggesting similar overall effects but potentially stronger in Roofed conditions.

Heterogeneity: Roofed has higher τ^2 (30.9621 vs. 26.9580) and H^2 (3711.06 vs. 1519.03), possibly due to more studies or diverse settings.

Subgroup Moderators:

Province: Significant in Roofed ($p=0.0251$) but not Open ($p=0.9407$), suggesting geographic variation is more relevant in Roofed settings.

Industry: Significant in both (Open: $p<0.0001$, Roofed: $p=0.0078$), but Open's R^2 (85.66%) is much higher than Roofed's (41.12%), indicating industry explains more variability in Open.

Year: Significant in Open ($p=0.0248$) but not Roofed ($p=0.3392$), suggesting temporal trends are relevant only in Open settings.

Study Count: Roofed ($k=24$) includes more studies than Open ($k=19$), which may contribute to higher heterogeneity but also more robust estimates.

Discussion

The present systematic review and meta-analysis, encompassing 19 studies in open environments ($n=1,452$ measurements) and 24 studies in roofed environments ($n=1,630$ measurements), provides a comprehensive assessment of occupational heat stress across Iranian industries over the last two decades. The findings reveal a pooled mean WBGT of 25.71°C (95% CI: 23.36–28.06) in open environments and 28.11°C (95% CI: 25.88–30.34) in roofed environments. These values, particularly in roofed settings, consistently exceed the Threshold Limit Values (TLVs) recommended by the American Conference of Governmental Industrial Hygienists (ACGIH) for moderate to heavy workloads, indicating a significant and pervasive occupational health hazard [1,2].

Magnitude of Heat Stress and Workforce Vulnerability

The mean WBGT in roofed environments (28.11°C) was notably higher than in open settings, a finding that underscores the critical role of inadequate ventilation, radiant heat from industrial processes (e.g., furnaces in steel and foundry industries), and limited convective cooling in

enclosed spaces. This aligns with prior research demonstrating that industries such as steel, glasswork, and melting/casting consistently exhibit the highest mean WBGT values [3-5]. The highest recorded individual study mean WBGT in the steel industry (40.20°C) reflects an extreme occupational exposure scenario that poses an imminent risk of heat-related disorders, including heat stroke, exhaustion, and syncope [6,7]. Such conditions are exacerbated when workers are required to wear heavy protective clothing or perform strenuous tasks, as factors like metabolic heat production and clothing insulation significantly influence heat strain but are often not fully accounted for by the WBGT index alone [8,9].

The observed mean WBGT values in our study are consistent with the global estimates reported by Flouris et al., who documented significant adverse effects of occupational heat strain on workers' health and productivity across multiple industries worldwide [10]. As highlighted in the recent ILO report on heat at work, occupational heat stress is not merely a localized issue but a global occupational health priority that demands immediate attention from policymakers, employers, and occupational health professionals [11].

The Persistent Challenge of Heterogeneity and the Need for Multifaceted Assessment

The extreme heterogeneity observed between studies ($I^2 > 99.9\%$) is a critical finding that highlights the vast climatic and occupational diversity within Iran. Subgroup analyses identified industry type as the most important explanatory factor, accounting for 85.66% of the variance in open environments and 41.12% in roofed settings. This variability complicates the interpretation of pooled estimates and emphasizes that a one-size-fits-all approach to heat stress management is inadequate [12,13]. Habibi et al., in a systematic review of climate-resilient strategies for outdoor workers, similarly emphasized the heterogeneity of exposure conditions across geographical regions and the need for region-specific interventions [14].

A significant limitation identified in the literature is the tendency for the WBGT index to misrepresent physiological strain under specific climatic conditions. In arid and semi-arid regions, the WBGT can underestimate the true heat load due to low wet-bulb temperatures despite high radiant heat, whereas in hot and humid coastal areas, it may overestimate the risk of heat strain [15-17]. This is because WBGT does not directly incorporate critical variables such as air velocity, metabolic rate, or individual physiological characteristics, which are integral to human thermoregulation [18,19]. A recent systematic review of 42 articles confirmed these limitations and concluded that indices such as UTCI and PHS can improve physiological prediction in specific contexts, while recommending climate-specific calibration and integration with physiological monitoring (e.g., heart rate) [20]. Therefore, reliance on a single environmental index may lead to inaccurate risk assessment and suboptimal intervention strategies.

Temporal Trends: Climate Change and Occupational Exposure

Meta-regression revealed a significant increasing trend in WBGT over time in open environments (coefficient = 0.68, $p = 0.0248$), while no significant trend was observed in roofed environments. This finding is consistent with broader research on the escalating impacts of climate change on occupational health [10,21]. As documented by Dasgupta et al., climate change is projected to significantly increase occupational heat exposure, particularly in tropical and subtropical regions, leading to substantial losses in labor productivity and increased health risks for workers [22]. In Iran specifically, climate projections indicate that heat stress will intensify, with zones currently hosting high-capacity steel production, such as the Persian Gulf coastal provinces (G4) and eastern desert regions (G1), facing the highest levels of future exposure [23]. With predicted temperature increases under various climate scenarios, WBGT levels are expected to rise, particularly in vulnerable zones, necessitating urgent climate-responsive policies and adaptation strategies to protect worker health and productivity [24]. Heidari et al. also predicted an approximately 2°C increase in air temperature by 2100 in different climates of Iran, which could exacerbate heat stress in open environments [9]. Esfandiari et al. also showed that climate change could reduce workers' productivity by up to 27%, highlighting the importance of monitoring and controlling heat stress [10].

Health Consequences of Occupational Heat Stress

The health implications of chronic and acute exposure to elevated WBGT levels are well-documented. Exposure to heat stress has significant effects on physiological parameters including heart rate, core body temperature, blood pressure, and hematological indices [25]. Akhlaghi Pirposhteh et al. demonstrated that chronic exposure to heat stress in foundry workers leads to decreased white blood cell count (1.02 ± 0.07 vs. $1.06 \pm 0.16 \times 1000/\mu\text{l}$, $p = 0.008$) and increased hemoglobin concentration (16.03 ± 0.03 vs. 15.31 ± 0.94 g/dl, $p = 0.018$) and hematocrit (44.52 ± 2.85 vs. $43.03 \pm 2.12\%$, $p = 0.042$), which can increase the risk of cardiovascular diseases [26]. Furthermore, Hoorfarasat et al. showed that the WBGT index has a higher correlation with physiological parameters (tympanic temperature with $r = 0.462$ and heart rate with $r = 0.456$) compared to the subjective HSSI index [27]. Zamanian et al., in a study of 387 farmers, demonstrated that with increasing WBGT, heart rate, skin temperature, and tympanic temperature increase, and WBGT has a significant correlation with skin temperature [28]. In the study by Ghotbi Ravandi et al. in the metal smelting industry, WBGT showed significant correlations with tympanic temperature ($r = 0.515$) and heart rate ($r = 0.458$), while HSSI showed weaker correlations with these parameters [5].

Research has also demonstrated a direct relationship between Universal Thermal Climate Index (UTCI) and mortality in Iranian metropolitan areas [29]. Under very strong and severe heat stress conditions (UTCI above 38°C and 46°C, respectively), mortality rates increase significantly. Fit of heat stress categories to mortality showed V-, U-, and J-shaped patterns, with increased mortality

observed from approximately 35°C upward (entering moderate heat stress range) [29]. These findings underscore the serious public health implications of rising heat stress levels in Iranian workplaces.

Emerging Alternatives and Complementary Assessment Strategies

Given the limitations of WBGT, there is a growing consensus on the need for hybrid or alternative approaches for comprehensive heat stress assessment. Recent validation studies have demonstrated that more novel and comprehensive indices can provide a more accurate prediction of physiological strain [30,31]. The Environmental Heat Strain Risk Assessment (EHSRA) index, which incorporates six main parameters including air temperature, globe temperature, wet temperature, airflow speed, metabolism, and clothing thermal resistance, demonstrated high diagnostic accuracy (AUC = 0.950) for predicting tympanic temperature [32]. Similarly, the Personal Heat Strain Risk Assessment (PHSRA) index, which integrates individual factors like age, body mass index, maximal aerobic capacity, and body surface area alongside environmental and occupational parameters, explains up to 77% of the variance in tympanic temperature ($R^2 = 0.77$) and demonstrated diagnostic accuracy with AUC = 0.947 [33]. The Observational-Perceptual Heat Strain Risk Assessment (OPHSRA) index, a questionnaire-based tool with 16 questions in four groups (environmental, occupational, management, and clothing factors), explained 69% of tympanic temperature variance ($R^2 = 0.69$) and demonstrated strong content validity (CVR = 0.793, CVI = 0.913) [34,35]. A comparative study by Moghaddas et al. confirmed that HSRA indices have significantly higher diagnostic accuracy compared to WBGT and PHS in predicting physiological responses in Iranian workers [36].

As summarized by Lee et al., a growing body of evidence supports the use of complementary indices and physiological monitoring to overcome the inherent limitations of environmental heat stress indices [37]. Furthermore, validation studies in Iran have shown that the Humidex index has a high correlation with WBGT ($R = 0.912$, $P < 0.001$) and can serve as a practical alternative, particularly in hot and humid environments [38]. Similarly, the Environmental Stress Index (ESI) demonstrated high intraclass correlation with WBGT ($ICC > 0.9$) in seven out of nine Iranian cities, with the exception of Ahvaz and Bandar Abbas due to extreme humidity and heat [39]. Afshari et al. showed that in the steel industry of Ahvaz, despite WBGT being higher than the permissible limits (mean 31°C), the physiological responses of workers were at a moderate level, and WBGT provided an overestimation of thermal strain [18]. Heidari and Golbabaei showed that in the humid regions of northern Iran, WBGT in some cases reaches 32.6°C, while the core body temperature of workers remains within the permissible range, indicating overestimation by WBGT in these conditions [17].

Comparison of Open and Roofed Environments

Comparison of the two environments showed that the mean WBGT in roofed environments (28.11°C) was higher than in open environments (25.71°C). This difference can be attributed to factors such as inadequate ventilation, heat accumulation in enclosed spaces, and the presence of heat sources such as furnaces in roofed industries. Furthermore, heterogeneity in roofed environments ($I^2 = 99.97\%$) was higher than in open environments ($I^2 = 99.93\%$), indicating greater diversity of conditions in enclosed environments. Subgroup analysis showed that province had a significant effect on WBGT in roofed environments ($QM = 23.32$, $p = 0.0251$, $R^2 = 33.17\%$), while this was not the case in open environments ($QM = 3.51$, $p = 0.9407$, $R^2 = 0.00\%$), likely due to the lesser influence of enclosed environments on regional climatic conditions.

Limitations of the WBGT Index and Its Implications

Numerous studies have shown that despite its widespread use, the WBGT index has significant limitations. These limitations include insufficient sensitivity to air velocity in hot and humid conditions, the need for a long time for temperature stabilization (at least 30 minutes), insufficient accuracy at high humidity levels, and the need for accurate estimation of metabolic rate and clothing thermal resistance [40]. Heidari et al. showed that the agreement between sweat rate (as an indicator of physiological strain) and WBGT is poor ($\kappa < 0.2$), and WBGT overestimates heat stress in arid and semi-arid regions of Iran [15]. Furthermore, Dehghan et al. in hot and humid conditions of the Persian Gulf showed that work-rest cycles based on WBGT are not suitable for heat stress management, and assessment based on physiological variables has higher validity [4].

In the study by Afshari et al. in traditional bakeries of Ahvaz, despite WBGT being above the permissible limits (mean 34.3°C), no significant correlation was found between WBGT and workers' physiological parameters, and WBGT could not accurately predict the actual thermal strain of workers [41]. This study recommended that WBGT is suitable as a screening index, but for precise management of heat stress in hot climates, complementary indices based on physiological responses are needed. Gharibi et al. also showed that in hot and dry environments, the use of indices based on physiological responses such as PHS can provide a more accurate estimate of the actual heat load, especially since WBGT underestimates in these conditions [19]. These findings indicate that relying solely on the WBGT index for judging the thermal conditions of workplaces, especially in the hot and humid climates of Iran, may lead to incorrect decisions.

Clinical and Policy Implications

Based on the findings of this study, the following recommendations are made for policymakers, occupational health professionals, and industry managers:

First: Revision of WBGT permissible limits in Iran based on the climatic conditions of each region and industry type, since the present study showed that WBGT in many Iranian industries is higher

than the current permissible limits [1,2]. Climate-specific threshold values should be developed considering the unique characteristics of Iran's diverse climatic zones [20].

Second: Simultaneous monitoring of physiological parameters (heart rate, tympanic temperature, sweat rate) alongside the WBGT index for more accurate assessment of thermal strain and prevention of overestimation or underestimation [15,17,28]. This combined approach has been recommended as a best practice in multiple systematic reviews [10,37].

Third: Adjustment of work-rest schedules based on workers' physiological responses rather than relying solely on the WBGT index, especially in hot and dry climates where WBGT may have significant error [4,20,42]. Morris et al. have proposed a hierarchy of sustainable interventions, from engineering controls (e.g., radiant heat shielding, forced ventilation) to administrative measures (e.g., work-rest schedules, heat acclimatization protocols) and personal cooling strategies [43].

Fourth: Design and implementation of engineering and management interventions appropriate for the climatic conditions of each region, including improvement of ventilation systems in roofed environments, creation of appropriate shading in open environments, and use of personal cooling equipment such as cooling vests, which studies have shown can significantly reduce the physiological strain index [44,45].

Fifth: Mandatory training of workers on recognizing early signs of heat stress, the importance of proper hydration, and self-care methods in hot environments, which can play an effective role in preventing heat-related complications [46,47].

Sixth: Special attention to climate change and global warming in long-term planning and adoption of adaptation strategies to this phenomenon, especially in open environments where the increasing trend of WBGT is evident [22,23]. Climate projections should be integrated into occupational health risk assessments and strategic planning [24].

Research Gaps and Future Perspectives

Despite the valuable findings of this study, several questions and research gaps remain that require investigation in future studies:

First: What is the efficacy and validity of alternative indices to WBGT (such as air enthalpy, TWL, UTCI, PHS, HSRA, Humidex, and ESI) in different climates of Iran, and which of these indices has a higher correlation with workers' physiological responses in different conditions? [20,30-34,38,39]

Second: What is the effect of long-term and chronic exposure to WBGT above the permissible limits on chronic occupational diseases, cardiovascular disorders, cognitive function, and workers' productivity in the long term? [10,22,26,29]

Third: Which engineering, management, and behavioral interventions are most effective in reducing WBGT and thermal strain in different industries with different climatic conditions, and which are more cost-effective? [43,44]

Fourth: Considering climate change and increasing air temperature in the coming decades, what impact will different temperature increase scenarios have on occupational exposure to heat stress in different industries in Iran, and what adaptation strategies should be adopted to cope with these changes? [22-24]

Fifth: Can new predictive models based on meteorological and physiological data predict heat stress with greater accuracy than current indices, and are these models applicable in different climatic conditions of Iran? [20,32-34,36]

Study Limitations

This study faced several limitations that should be considered when interpreting the results. The first limitation was the search for articles only in Persian and English, which may have led to the loss of some valuable studies in other languages. The second limitation was the lack of access to raw data from some studies, which made it difficult to fully extract the required information. The third limitation was the very high heterogeneity of studies ($I^2 > 99.9\%$), which, despite subgroup analysis and meta-regression, still left a significant portion unexplained. The fourth limitation was the wide diversity of WBGT measurement methods in different studies (use of different devices, different measurement heights, and different sampling times), which may have affected the accuracy and comparability of results. The fifth limitation was the difference in the types of industries and working conditions, which, despite subgroup analysis, did not allow full control over all confounding variables. Despite these limitations, sensitivity analysis showed that the overall results of the study were sufficiently robust.

Conclusion

This meta-analysis confirms that occupational heat stress in Iranian workplaces poses a serious and escalating threat to workers' health, with mean WBGT values in both open (25.71°C) and roofed (28.11°C) environments consistently exceeding recommended limits and showing a significant increasing trend in open environments over the past two decades. The extreme heterogeneity across industries and climates emphasizes the need for region-specific interventions rather than a uniform approach. The well-documented limitations of the WBGT index, particularly

in hot and humid conditions, highlight the necessity of adopting combined approaches integrating environmental monitoring with physiological surveillance and validated alternative indices such as HSRA, Humidex, and ESI. Urgent actions are required including revision of national permissible limits, implementation of engineering and administrative controls, mandatory worker training, and development of climate-adaptive occupational health policies to protect the health, safety, and productivity of the Iranian workforce.

Data Availability Statement

The data generated and/or analyzed during this study are available from the corresponding author upon reasonable request.

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