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## Research Article

**Keywords:** Occupational Exposure, Heat Stress, Occupational Health, Physiologically Equivalent Temperature, Spatial Analysis

**Posted Date:** October 7th, 2026

**DOI:** <https://doi.org/10.21203/rs.3.rs-10862601/v1>

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**Additional Declarations:** No competing interests reported.

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# Long-Term Physiologically Equivalent Temperature Trends and Climate-Related Occupational Heat Exposure Across Industrial Sectors in Iran

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## Abstract

**Background:** Climate change is intensifying environmental heat exposure, posing an increasing challenge to occupational health, particularly in climate-sensitive industries. Despite growing evidence linking heat stress to adverse occupational outcomes, nationwide assessments integrating physiologically meaningful thermal conditions with industrial geography remain limited. This study aimed to characterize the spatial distribution of climate-related occupational heat exposure across Iran by integrating a 66-year (1959–2025) Physiologically Equivalent Temperature (PET) climatology with the national distribution of major industrial sectors.

**Methods:** A nationwide ecological geospatial analysis was conducted using long-term PET climatology derived from meteorological observations and classified according to established physiological thermal stress thresholds. Spatial distributions of major industrial sectors, including mining, metal processing, petroleum and petrochemical industries, coke production, cement, textile manufacturing, agriculture, and food processing, were integrated with PET classes using a GIS-based overlay framework to characterize sector-specific occupational heat exposure patterns across Iran.

**Results:** Nationwide geospatial integration of industrial infrastructure with a 66-year PET climatology revealed pronounced spatial concordance between major industrial activities and regions characterized by elevated physiological thermal stress. Across the national industrial landscape, most facilities were situated within PET values  $\geq 35^{\circ}\text{C}$ , corresponding to strong ( $35\text{--}41^{\circ}\text{C}$ ) or extreme ( $>41^{\circ}\text{C}$ ) heat stress, whereas thermoneutral conditions ( $18\text{--}23^{\circ}\text{C}$ ) were comparatively uncommon. Mining, metal processing, petroleum and petrochemical industries exhibited the greatest concentration within severe-to-extreme PET environments. By contrast, agricultural activities demonstrated greater representation within thermoneutral and moderate heat-stress classes, while coke manufacturing displayed a comparatively distinct thermal exposure profile relative to other petroleum-related industries. Overall, the analysis identified substantial thermo-geographical heterogeneity in occupational heat exposure, delineating sector-specific patterns of industrial thermal vulnerability across Iran.

**Conclusion:** Integrating long-term PET climatology with industrial geography provides a physiologically grounded framework for nationwide ecological characterization of occupational heat exposure and industrial thermal vulnerability. By translating long-term biometeorological conditions into spatially explicit patterns of industrial heat exposure, this study advances occupational biometeorology, spatial epidemiology, and environmental exposure science while establishing a scalable methodological framework for national climate-related occupational heat assessment.

**Keywords:** Occupational Exposure; Heat Stress; Occupational Health; Physiologically Equivalent Temperature; Spatial Analysis.

## 1. Background

Human health is inherently influenced by climatic factors, including ambient temperature, relative humidity, and atmospheric pressure (Kunst et al., 1994). Changes in climatic conditions affect multiple dimensions of human life, as well as economic and social systems, including public health, water resources, and agriculture (Jalali et al., 2020). Extreme weather events, encompassing climatic phenomena such as heatwaves, cold spells, droughts, floods, wildfires, and storms (Beillouin et al., 2020; McMichael, 2015), are associated with substantial adverse consequences, including widespread damage, increased morbidity and mortality, and significant socioeconomic disruption (Beillouin et al., 2020).

Heatwaves are prolonged periods of abnormally high temperatures that occur more frequently in hot and arid climates (Cheng et al., 2019). Climate change is altering long-term climatic patterns and has contributed to an increase in the frequency, intensity, and duration of heatwaves worldwide (Hashim & Hashim, 2016). The duration of heatwaves is projected to increase by 2 to 10 days for every 1°C rise in global temperature (Perkins-Kirkpatrick & Gibson, 2017). Previous studies have reported that both heatwaves and cold spells occur frequently in Iran, a country characterized predominantly by arid and semi-arid climatic conditions (Ahmadnezhad et al., 2013). Furthermore, because Iran is located within the Middle East and North Africa (MENA) region one of the world's most climate-vulnerable regions ongoing climate change is expected to exacerbate recurrent and severe droughts, intensify water scarcity, and increase the frequency and intensity of heatwaves across the country (Mansouri Daneshvar et al., 2019; Vaghefi et al., 2019).

Furthermore, since the second half of the twentieth century, the global population has grown substantially, with urban areas increasingly preferred over rural regions because of greater employment opportunities and improved access to services. According to the United Nations (UN), approximately 30% of the world's population resided in urban areas in 1950, and this proportion is projected to increase to 60% by 2030 (Desa, 2018). This rapid urban expansion, driven by the conversion of rural land into urban environments and compounded by climate change, has emerged as one of the most pressing global challenges of the twenty-first century (Mukherjee & Debnath, 2020; Schneider et al., 2010). Population growth, together with rapid urbanization, the widespread use of

impervious building materials, the loss of green spaces, and intensified anthropogenic activities, has substantially altered local climatic conditions, particularly ambient temperature, thereby adversely affecting human health and quality of life (Brousse et al., 2019; Equere et al., 2020; Santamouris, 2020; Wu et al., 2022). Consequently, a comprehensive report on the health impacts of climate-related hazards was published during the past decade (McMichael, 2003), and the role of climatic conditions in the emergence and transmission of infectious diseases has long been recognized (Amelung et al., 2007). Furthermore, the influence of climatic conditions on human physiological heat stress has become a major focus of research in recent decades, attracting considerable attention from investigators worldwide, including those in Iran.

Heat and cold stress arise from exposure to extreme thermal environments and are classified as extreme weather events, defined as rare meteorological phenomena that deviate substantially from normal climatic conditions. Individuals are frequently exposed to these thermal extremes during routine daily activities or occupational tasks. Such exposures can markedly impair physical performance and disrupt physiological function. When the body is unable to dissipate excess heat through sweating and other thermoregulatory mechanisms, serious adverse health consequences may occur. Consequently, individuals are often required to reduce their physical workload to mitigate the detrimental effects of heat stress (Parsons, 2007).

During the autumn and winter seasons, the lowest values of the Physiologically Equivalent Temperature (PET), indicative of severe cold stress, have been reported in high-altitude regions (FALLAH et al., 2015). At higher elevations, the combined effects of lower atmospheric moisture and hypobaric environmental conditions increase the risk of dehydration, reduce metabolic rate, and impair peripheral tissue perfusion. Under conditions conducive to the development of acute mountain sickness (AMS), these physiological alterations may further increase susceptibility to altitude-related illness. Accordingly, the health impacts of thermal stress have become a major focus of scientific investigation over recent decades and are now widely recognized as an important public health and occupational health concern (FERRIS et al., 1998; Kjellstrom, 2009; Poumadere et al., 2005).

Studies examining the role of climatic conditions in mortality have consistently demonstrated the adverse health effects of thermal stress. A study conducted in Athens in 2012, using bioclimatic comfort indices, reported a significant linear association between mortality and bioclimatic thermal stress (Nastos & Matzarakis, 2012). Similarly, a 2025 study conducted in Madrid assessed the health impacts of elevated temperatures using the Vegetation Proportion (VP), Urban Index (UI), and Heat Stress Index (HSI). The findings showed that areas with limited vegetation cover experienced greater heat stress and were associated with a higher risk of several types of cancer and chronic obstructive pulmonary disease (COPD) (Puga-Bonilla et al., 2025). Furthermore, a meta-analysis published in 2024 evaluating the health effects of heatwaves and cold spells in Iran demonstrated that exposure to extreme temperatures, including both heat and cold, significantly increased the risks of all-cause and cardiovascular mortality, underscoring the need for effective interventions to reduce exposure to extreme temperatures during heatwave events (Hadei et al., 2024). In addition, evidence indicates an inverse relationship

between ambient air temperature and plasma fibrinogen concentration, with elevated fibrinogen levels being associated with an increased incidence of seasonal respiratory infections (Halonen et al., 2010). Consequently, thermal stress is widely recognized as one of the most important environmental determinants of human health. Therefore, comprehensive information on the spatial and temporal distribution of physiological thermal stress across Iran is essential for developing evidence-based guidelines and occupational heat-health strategies to protect the health of workers in industrial settings.

Therefore, the present study aimed to integrate long-term PET trends with the spatial distribution of major industrial sectors to conduct a nationwide spatial assessment of climate-related occupational heat risk across Iran. By identifying geographic hotspots of occupational thermal exposure, this study provides a scientific basis for climate-resilient occupational health policies, targeted heat adaptation strategies, and evidence-informed workforce protection.

## **2. Methods**

### **2.1. Study Area and Climatic Data**

This nationwide ecological geospatial study was conducted to characterize the long-term spatial distribution of human physiological thermal stress across Iran using the Physiologically Equivalent Temperature (PET) index. Climatic data were obtained from 40 synoptic meteorological stations representing the country's major climatic regions, including Mashhad, Torbat-e Heydarieh, Sabzevar, Birjand, Zabol, Zahedan, Chabahar, Kerman, Jask, Bandar Abbas, Bandar Lengeh, Fasa, Shiraz, Yazd, Isfahan, Shirkuh, Bushehr, Abadan, Ahvaz, Dezful, Khorramabad, Kermanshah, Arak, Kashan, Semnan, Tehran, Hamedan, Qazvin, Zanjan, Shahroud, Gorgan, Babolsar, Nowshahr, Ramsar, Rasht, Bandar-e Anzali, Tabriz, Urmia, and Khoy. A common observation period from 1959 to 2025 was adopted to ensure temporal consistency across all monitoring stations.

Meteorological data were obtained from the Iran Meteorological Organization (IRIMO). The climatic variables used to calculate the PET index included monthly mean daily air temperature (°C), monthly mean daily relative humidity (%), monthly mean daily maximum air temperature (°C), monthly mean daily minimum relative humidity (%), monthly total precipitation (mm), monthly mean daily sunshine duration (h), monthly mean daily wind speed (km/h), and vapor pressure (hPa). Prior to analysis, all meteorological records underwent comprehensive quality-control procedures to assess data completeness, consistency, and temporal homogeneity. These variables constituted the primary climatic inputs for estimating long-term physiological thermal conditions and subsequent spatial analyses across Iran.

### **2.2. Assessment of Physiological Thermal Stress**

Human physiological thermal stress was assessed using the PET, one of the most widely applied thermo-physiological indices in human biometeorology. PET is derived from the Munich Energy Balance Model for Individuals (MEMI) and provides an integrated assessment of the outdoor thermal environment by combining the

effects of air temperature, relative humidity, wind speed, and mean radiant temperature while accounting for key physiological characteristics, including metabolic rate and clothing insulation. Owing to its strong physiological foundation, clear physical interpretation, and applicability across diverse climatic conditions, PET has been extensively used in studies of outdoor thermal comfort, occupational heat exposure, environmental epidemiology, and climate-related health risk assessment. The theoretical framework of PET is based on the human energy balance equation, which assumes that thermal equilibrium is achieved when total heat gain equals total heat loss:

$$M+W+R+C+ED+ERE+ESW+S=0$$

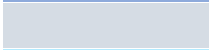
where all energy fluxes are expressed in  $W/m^2$ . In this equation, M denotes metabolic heat production, W external mechanical work, R net radiant heat exchange, C convective heat exchange, ED latent heat loss through water diffusion across the skin, ERE respiratory heat exchange, ESW evaporative heat loss through sweating, and S the rate of body heat storage. Positive values indicate net heat gain, whereas negative values indicate net heat loss. Under normal physiological conditions, metabolic heat production (M) is positive, whereas external work (W) and the evaporative and respiratory heat-loss components (ED, ERE, and ESW) generally contribute to body heat dissipation.

Under the standard reference conditions described by Matzarakis (2010), PET represents the air temperature of a standardized indoor environment that produces the same physiological response as the actual outdoor environment. These reference conditions assume light physical activity (80 W), clothing insulation of 0.9 clo, and a standardized indoor thermal environment. Clothing insulation was expressed in clo, where 1 clo corresponds to a thermal resistance of  $0.155 \text{ m}^2 \cdot ^\circ\text{C}/\text{W}$ . The thermal insulation values assigned to the clothing ensembles used in this study are presented in Table 3. PET values were interpreted according to the internationally recognized thermal perception and physiological stress classification proposed by Matzarakis et al. (Matzarakis et al., 1999), as presented in Table 1.

Meteorological variables required for PET estimation were obtained at the standard biometeorological reference height of 1.5 m above ground level from the selected synoptic meteorological stations. Missing or incomplete meteorological records were reconstructed using linear regression imputation to ensure the temporal completeness and consistency of the long-term climatic time series. PET was calculated using the RayMan model, a validated human biometeorological model based on the MEMI framework. Air temperature, relative humidity, and wind speed were obtained directly from meteorological observations, whereas the mean radiant temperature the principal radiative determinant of human thermal stress was estimated by the RayMan model because of its complex dependence on shortwave and longwave radiation fluxes, sky-view geometry, and surrounding surface characteristics.

**Table 1.** PET classification of human thermal perception and physiological stress levels

| Physiological Stress Category | Thermal Perception | PET ( $^\circ\text{C}$ ) | Map Color |
|-------------------------------|--------------------|--------------------------|-----------|
|-------------------------------|--------------------|--------------------------|-----------|

|                      |               |       |                                                                                     |
|----------------------|---------------|-------|-------------------------------------------------------------------------------------|
| Extreme cold stress  | Very cold     | < 4   |  |
| Strong cold stress   | Cold          | 4–8   |  |
| Moderate cold stress | Cool          | 8–13  |  |
| Slight cold stress   | Slightly cool | 13–18 |  |
| No thermal stress    | Comfortable   | 18–23 |  |
| Slight heat stress   | Slightly warm | 23–29 |  |
| Moderate heat stress | Warm          | 29–35 |  |
| Strong heat stress   | Hot           | 35–41 |  |
| Extreme heat stress  | Very hot      | > 41  |  |

### 2.3. Spatial Interpolation and GIS Mapping

Following PET estimation, the frequency of each physiological thermal stress category was determined for all synoptic meteorological stations. Seasonal spatial distributions of PET were generated using the Inverse Distance Weighting (IDW) interpolation method within a Geographic Information System (GIS) environment to produce continuous thermal surfaces across Iran. These interpolated surfaces were subsequently used to characterize the long-term spatial distribution of physiological thermal stress and served as the basis for integrating PET maps with the spatial distribution of major industrial facilities to identify climate-related occupational heat risk hotspots. IBM SPSS Statistics was used for data preprocessing, quality control, missing-data assessment, variable normalization, and statistical analyses.

### 2.4. Industrial Distribution and Climate-Related Occupational Heat Risk Assessment

The spatial distribution of major industrial facilities across Iran was integrated with the seasonal PET maps to identify areas of elevated climate-related occupational heat exposure and thermal stress risk. Geospatial data on the location of major industrial sectors were compiled and overlaid onto the interpolated PET surfaces within a GIS framework. This spatial overlay procedure enabled the identification of industrial zones exposed to different classes of physiological thermal stress, with particular emphasis on areas experiencing strong, very strong, and extreme heat stress during the warm season.

Given that August represents the period of peak thermal load across most regions of Iran, the August PET distribution was selected as the reference condition for occupational heat exposure assessment. Industrial facilities located within high-PET zones were classified as having elevated potential for occupational heat strain and climate-sensitive work-related heat exposure. The spatial concordance between industrial distribution and PET-derived thermal stress classes was then used to delineate occupational heat risk hotspots and to provide a geospatial basis for assessing the vulnerability of workers in major industrial regions. This integrated spatial analytical approach supports the identification of priority areas for occupational heat risk management, climate adaptation strategies, and evidence-based workplace heat-health interventions.

## **2.5. Statistical Analysis**

Statistical analyses were conducted using IBM SPSS Statistics, while spatial analyses were performed in a GIS environment. Descriptive statistics were used to summarize meteorological variables and PET across stations and seasons. Missing meteorological data were reconstructed using linear regression imputation to ensure temporal continuity of the climatic time series. Normality of continuous variables was assessed using standard statistical tests. PET values were classified into established physiological thermal stress categories, and their frequencies were calculated by station and season. Spatial distribution patterns were evaluated using the IDW interpolation method to generate continuous surfaces of thermal stress across Iran. These surfaces were integrated with the spatial distribution of industrial facilities to identify climate-related occupational heat exposure hotspots. All analyses were performed using a two-sided approach and reported in accordance with standard conventions in environmental and occupational epidemiology.

## **3. Results**

### **3.1. Spatial distribution of physiological thermal stress across spring months**

In April, PET-based thermal stress showed strong physio-climatic gradients across Iran. Cold stress was confined to high-altitude northern and northwestern regions ( $\approx 33\%$ ;  $\sim 778,424 \text{ km}^2$ ), including Hamadan, Zanzan, Urmia, Khoy, and Tabriz. Heat stress (moderate to severe) dominated southern coastal and southeastern lowlands along the Persian Gulf and Gulf of Oman ( $\approx 11\text{--}12\%$ ;  $\sim 189,670 \text{ km}^2$ ). Thermal comfort prevailed over  $47.7\%$  ( $\sim 778,424 \text{ km}^2$ ), mainly across the Zagros–Alborz orographic belt and central uplands, while mild heat stress covered  $29\%$  ( $\sim 474,142 \text{ km}^2$ ) in low-elevation arid zones. In May, PET distributions shifted under enhanced radiative forcing, rising air temperature, reduced precipitation, and Azores High dominance. Severe heat stress ( $\text{PET} > 41^\circ\text{C}$ ) expanded to  $33\%$  ( $\sim 538,483 \text{ km}^2$ ), concentrated in southern and southwestern lowlands. Moderate heat stress ( $29^\circ\text{C} < \text{PET} < 35^\circ\text{C}$ ) accounted for  $11.7\%$  ( $\sim 187,652 \text{ km}^2$ ), extending across southern Iran. Thermal comfort contracted to  $7.6\%$  ( $\sim 124,379 \text{ km}^2$ ) in northwestern highlands, while mild heat stress remained the dominant class ( $47.7\%$ ;  $\sim 778,264 \text{ km}^2$ ).

In June, the complete disappearance of cold stress coincided with marked contraction of thermal comfort zones. Severe heat stress increased to  $48.1\%$  ( $\sim 784,491 \text{ km}^2$ ), encompassing the southern coastal belt, Jazmurian Basin, and Dasht-e Lut. Moderate heat stress dominated the remaining  $51.4\%$  ( $\sim 837,353 \text{ km}^2$ ), while mild heat stress became marginal ( $0.43\%$ ;  $\sim 7,080 \text{ km}^2$ ). In July, synoptic-scale transition to a summer regime characterized by surface thermal low development and intensified subtropical anticyclonic circulation aloft resulted in near-continuous heat-stress dominance across Iran (fig.1).

### **3.2. Spatial distribution of physiological thermal stress during summer months**

In July, synoptic-scale atmospheric conditions characterized by a surface thermal low, strengthened subtropical anticyclonic circulation aloft, and persistent Azores High dominance resulted in nationwide prevalence of heat-

related thermal stress. Cold stress was absent across Iran. Only a very limited area in high-altitude northern regions (~0.17%; 2,902 km<sup>2</sup>) exhibited mild heat stress, while the remainder of the country experienced moderate to very severe heat stress. Very severe heat stress (PET > 41°C) was the dominant class, covering 78.6% of the national territory (1,281,446 km<sup>2</sup>), primarily concentrated in the Khuzestan Plain, southern coastal belt, Dasht-e Lut, Jazmurian Basin, and Sistan region. In August, very severe heat stress persisted over extensive areas, including the southern foothills of the Zagros, eastern and southeastern Iran, the Dasht-e Kavir, and parts of the Caspian coastal zone, accounting for 59.6% of the country (972,183 km<sup>2</sup>). Moderate heat stress covered 40.3% (656,812 km<sup>2</sup>) and was mainly distributed across northern, northeastern, northwestern, and central regions.

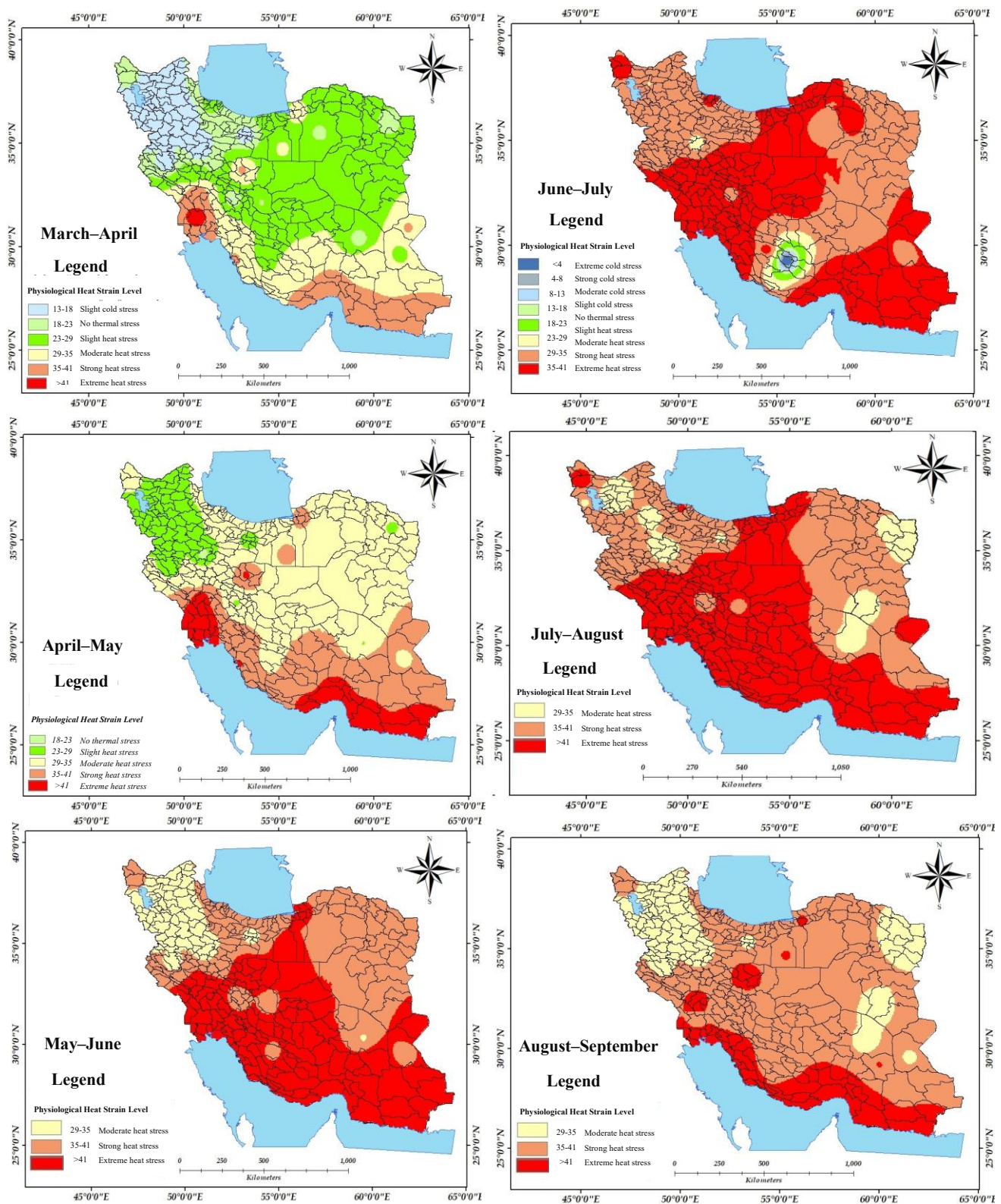


**Fig 1.** Seasonal spatial distribution of Physiologically Equivalent Temperature (PET)-derived physiological heat stress classes across Iran (March–September).

In September, reduced solar radiation was associated with a gradual decline in thermal stress intensity. No severe or very severe heat stress ( $PET > 35^{\circ}\text{C}$ ) was observed north of  $30^{\circ}\text{N}$  latitude. Very severe heat stress was confined to 13.5% of the national area (220,450  $\text{km}^2$ ), limited to the Khuzestan Plain and a narrow southern coastal strip (Bushehr, Abadan, Bandar Lengeh, Jask, and Chabahar). Moderate to severe thermal conditions dominated 57.9% of the territory (944,335  $\text{km}^2$ ), covering most remaining regions. Overall, strong altitudinal and latitudinal gradients governed the spatial distribution of physiological thermal stress across Iran, with a concurrent presence of thermally comfortable high-elevation zones and extreme heat stress in southern lowlands, reflecting persistent climatic heterogeneity during the warm season (fig. 1).

### **3.3. Spatial distribution of physiological thermal stress during autumn months**

In October, thermoneutral conditions peaked annually, covering 43.5% of Iran (709,275  $\text{km}^2$ ) under synoptic thermal moderation and subtropical anticyclone retreat. These zones dominated northern, western, and northeastern highlands (e.g., Tabriz, Urmia, Tehran, Rasht, Mashhad, Zahedan, Kerman), while mild thermal stress occupied 41.1% (669,623  $\text{km}^2$ ) across lowlands. Moderate heat stress was confined to 15.3% (249,904  $\text{km}^2$ ), mainly along the southern coastal belt (Persian Gulf–Hormuz–Oman Sea).

In November, radiative cooling and large-scale circulation shifts expanded cold stress dominance. Mild cold stress covered 55.3% (900,777  $\text{km}^2$ ) and moderate cold stress 13.1% (214,396  $\text{km}^2$ ), concentrated in high-altitude belts of the Zagros, Alborz, Aladagh, and Kopet Dag. The thermoneutral zone contracted to 20% (326,576  $\text{km}^2$ ), displaced to a narrow southwest–southeast corridor. Mild heat stress persisted only along southern coastal margins (11.4%; 187,114  $\text{km}^2$ ). In December, continental high-pressure systems established a cold-dominated regime with no heat stress ( $PET > 23^{\circ}\text{C}$ ). Thermal comfort was limited to 12% (196,733  $\text{km}^2$ ) in southern coastal areas. Very severe cold stress ( $<4^{\circ}\text{C}$  PET) affected 4% (78,493  $\text{km}^2$ ), while severe cold stress ( $4\text{--}8^{\circ}\text{C}$  PET) extended to 19% (321,428  $\text{km}^2$ ), encompassing major urban and mountainous regions (e.g., Tehran, Mashhad, Hamedan, Kermanshah). Cold stress constituted the dominant bioclimatic condition nationwide (fig. 2).

### **3.4. Spatial distribution of physiological thermal stress during winter months**

In January, large-scale synoptic circulation dominated by Siberian–European anticyclones, Siberian–Icelandic hybrid systems, and Siberian high-pressure cells (32%, 23%, and 17%, respectively) induced pervasive continental cold advection. Very severe cold stress ( $<4^{\circ}\text{C}$  PET) extended over 80.8% of Iran (1,176,570  $\text{km}^2$ ), while latitudes  $>33^{\circ}\text{N}$  were fully exposed to severe-to-extreme cold stress, covering 75% of the national territory (1,230,051  $\text{km}^2$ ). Mild cold stress was confined to southwestern lowlands (17.9%; 291,597  $\text{km}^2$ ), whereas thermoneutral conditions persisted only in a narrow southeastern maritime corridor influenced by oceanic air masses.

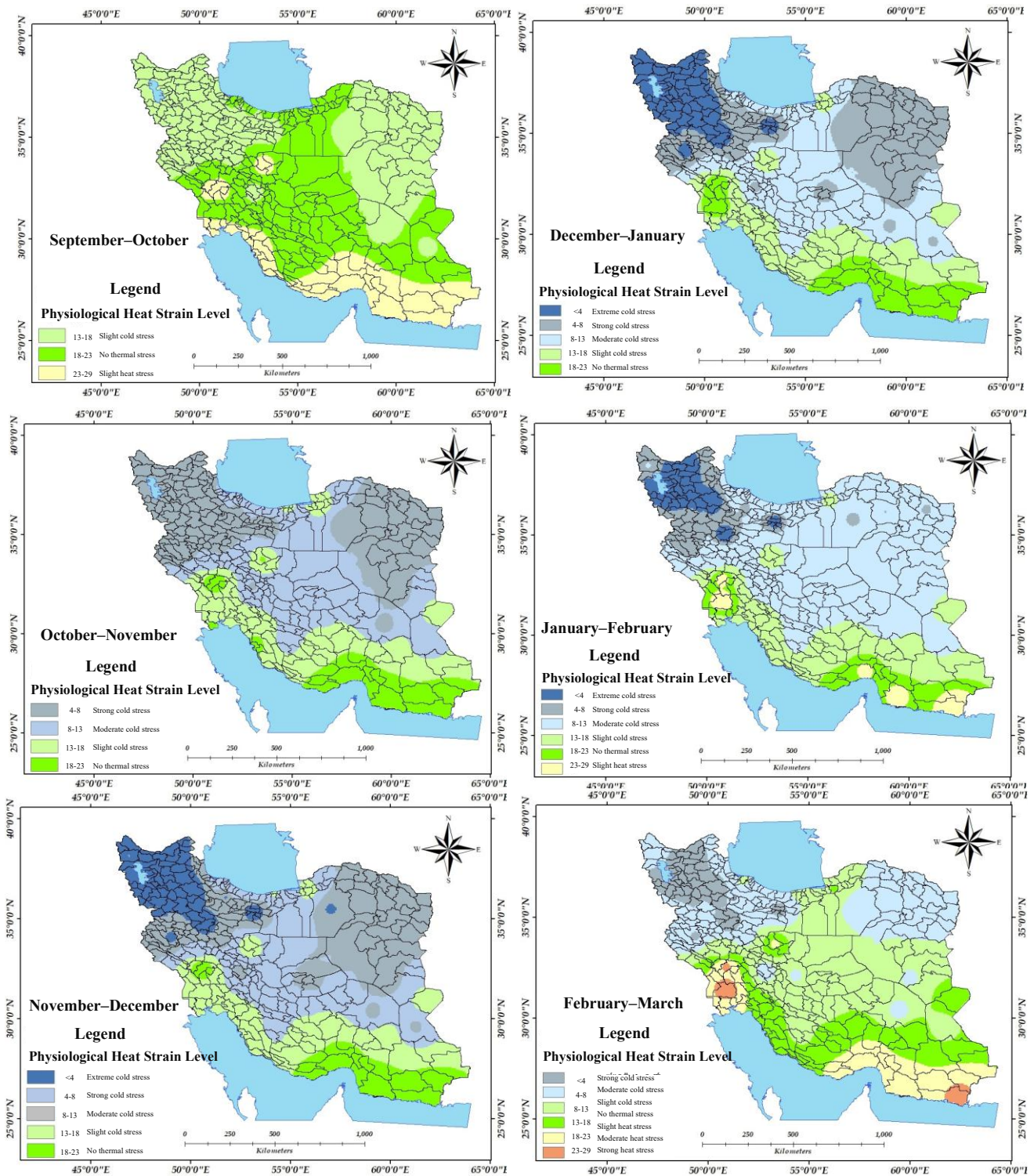


**Fig 2.** Seasonal spatial distribution of Physiologically Equivalent Temperature (PET)-derived physiological heat stress classes across Iran (September–March)

In February, sustained wintertime anticyclonic regimes maintained a cold-dominated bioclimatic structure. Very severe cold stress occupied 4.1% (68,277 km<sup>2</sup>), severe cold stress 15.2% (249,061 km<sup>2</sup>), and mild cold stress 45.8% (747,307 km<sup>2</sup>), representing the dominant national class. Thermoneutral conditions (14.1%; 230,478 km<sup>2</sup>)

remained restricted to southern and southeastern coastal lowlands (e.g., Ahvaz, Abadan, Chabahar, Jask, Bandar Abbas). In March, increased solar elevation and seasonal radiative forcing induced a northward shift of thermally neutral zones. Thermoneutral conditions expanded to 22% (359,128 km<sup>2</sup>), mainly across southern and central Iran. Mild cold stress (8–13°C PET) dominated 48.5% (791,353 km<sup>2</sup>), while moderate cold stress (4–8°C PET) covered 17.7% (289,502 km<sup>2</sup>). Cold stress persisted as the prevailing regime, albeit with reduced spatial intensity relative to mid-winter conditions (fig.2).

### **3.5. Food Industries Across PET-Based Heat Stress Classes**

Fig. 3 depicts the spatial distribution of food industries across PET-based heat stress classes. Although facility distribution varied among subsectors, most establishments were concentrated within severe-to-extreme heat stress zones during August, whereas thermoneutral and cold-stress conditions were confined to high-altitude northwestern areas. Flour milling and biscuit manufacturing exhibited the broadest geographic coverage and the highest facility density, followed by dairy and sugar industries, all predominantly clustered within severe heat stress regions. In contrast, chocolate and cocoa manufacturing showed a more localized distribution, while canned food production exhibited the lowest facility density despite a comparable thermal exposure pattern.

Pasta manufacturing was widely distributed but less spatially concentrated than flour and dairy industries, with only a small proportion of facilities occurring under thermoneutral or mild heat stress conditions. Overall, severe heat stress constituted the dominant PET class across all food-processing subsectors, with inter-subsector variation primarily reflecting differences in facility density rather than thermal exposure profiles.

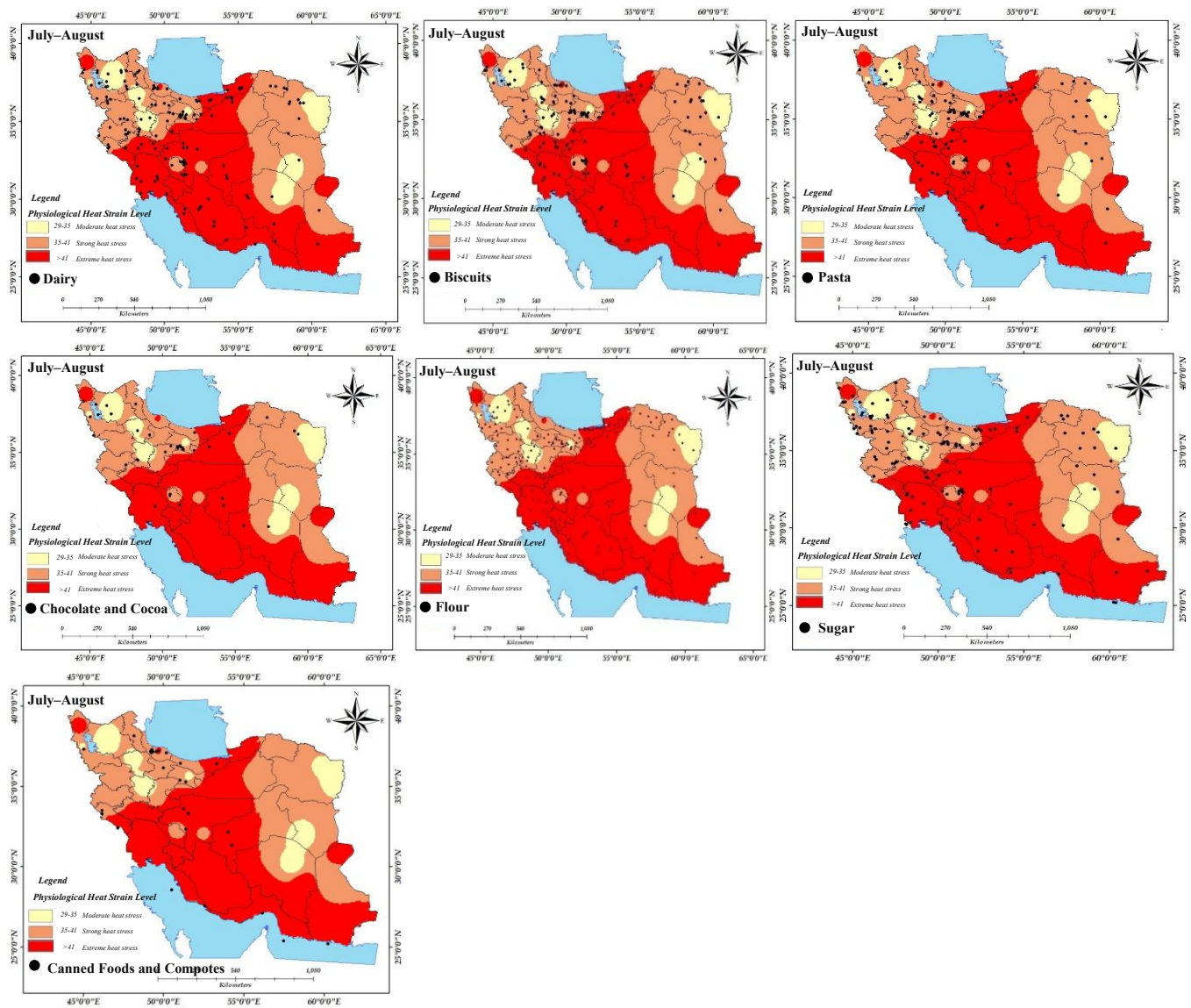


**Fig 3.** Spatial concordance between Food facilities and PET-derived physiological heat stress classes across Iran during August.

### 3.6. Paper and Agriculture Industries Across PET-Based Heat Stress Classes

The spatial distribution presented in Fig. 4 indicates that paper and pulp industries were sparsely distributed, with facilities clustered mainly across northern, central, and southwestern Iran. The vast majority of establishments were situated within PET-defined severe heat stress zones, while only a few occurred under moderate or thermoneutral conditions in the northwestern highlands and isolated northeastern regions. Overall, severe heat stress predominated, with minimal representation across lower PET heat stress classes.

As illustrated in Figure 4, agricultural industries exhibited a pronounced spatial concentration within regions classified as strong (35–41 °C) and extreme (>41 °C) PET-derived physiological heat stress, with only sparse

representation across thermoneutral or lower-stress environments. Industrial facilities were predominantly distributed throughout the southern, southwestern, central, and southeastern regions of Iran, where extreme physiological heat stress constituted the dominant thermal exposure category. Additional clusters occurred within adjacent areas characterized by strong heat stress, whereas relatively few agricultural facilities were located in regions experiencing moderate heat stress (29–35 °C). Thermoneutral conditions (18–23 °C) were restricted to isolated mountainous areas in the northwest, west, and northeast, encompassing only a negligible proportion of agricultural establishments. No appreciable spatial overlap was observed with PET-defined cold-stress categories. Overall, the agricultural sector displayed a markedly skewed thermal exposure profile, with severe-to-extreme physiological heat stress overwhelmingly predominating, indicating one of the highest levels of potential occupational heat exposure among the industrial sectors evaluated.

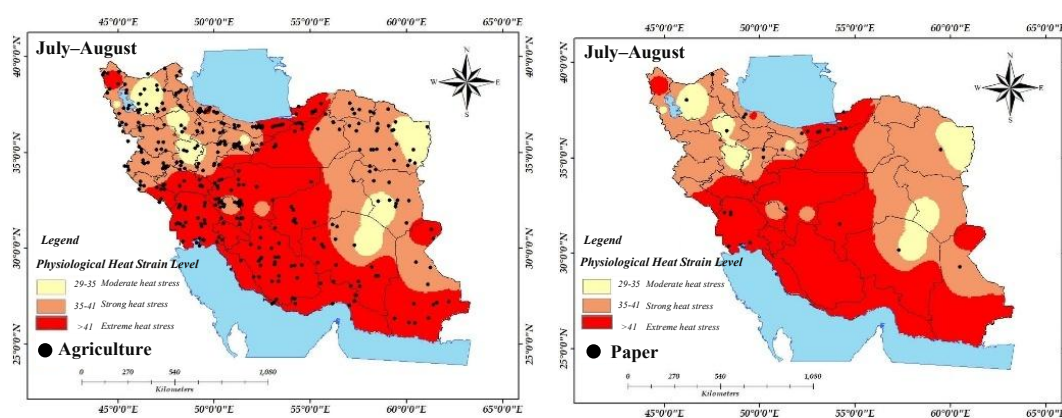


**Fig 4.** Spatial concordance between Paper and Agriculture facilities and PET-derived physiological heat stress classes across Iran during August

### 3.7. Textile, and leather Industries Across PET-Based Heat Stress Classes

As illustrated in Fig. 5, textile, leather, and clothing industries exhibited marked spatial heterogeneity, with textile manufacturing showing substantially greater facility density and geographic coverage than leather processing. Despite this difference, both subsectors were predominantly concentrated within PET-defined severe heat stress zones, whereas only a limited number of establishments overlapped with moderate or thermoneutral conditions in the northwestern highlands and isolated northeastern regions. Overall, severe heat stress predominated across both subsectors, with textile manufacturing accounting for the greater occupational heat exposure burden because of its higher concentration of facilities in high-PET regions.

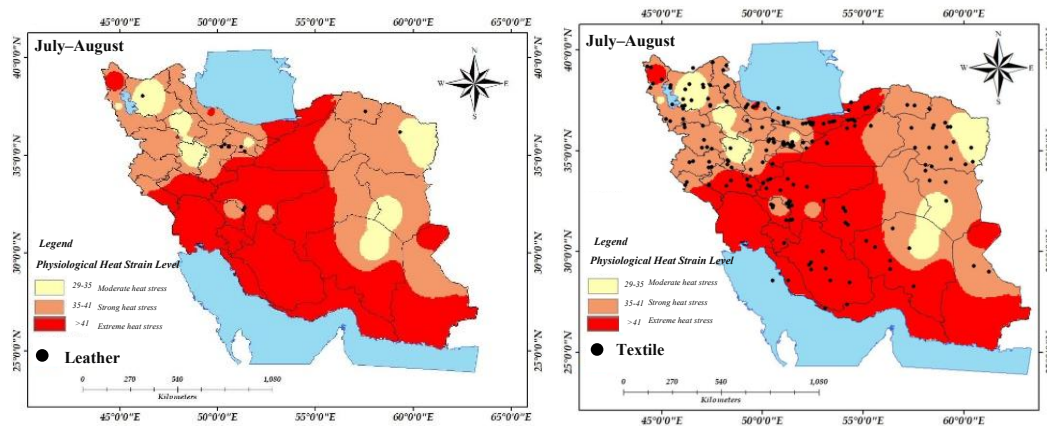


**Fig 5.** Spatial concordance Textile, and leather facilities and PET-derived physiological heat stress classes across Iran during August

### 3.8. Oil, Gas, and Petrochemical Industries Across PET-Based Heat Stress Classes

As illustrated in Fig. 6, the oil, gas, and petrochemical industries were predominantly concentrated within regions classified as severe to extreme PET-derived heat stress during August. Petrochemical complexes, upstream oil fields, gas facilities, refineries, and petroleum distribution infrastructures were spatially clustered across the southern, southwestern, and central industrial corridors, where PET values were overwhelmingly assigned to the highest thermal stress categories. In contrast, only a limited number of facilities were located within thermoneutral or mild heat-stress zones, while cold-stress conditions were absent. Marked heterogeneity was evident across industrial subsectors. The National Iranian Gas Company exhibited the widest geographic distribution and the greatest occupational heat-exposure burden, with most facilities situated in severe or extreme PET classes. A comparable pattern was observed for the National Iranian Oil Company, whose upstream production sites were concentrated across southern and southwestern provinces, with only isolated installations extending into lower PET categories in northern Iran. The Southern Oil Company demonstrated the most homogeneous exposure profile, with nearly all operational sites located within severe-to-extreme heat-stress zones.

The National Iranian Oil Refining and Distribution Company and the petrochemical industry displayed similar spatial exposure patterns, with facilities primarily distributed across high PET zones, although a small proportion occurred within moderate or thermoneutral environments in northwestern and north-central Iran. By contrast, Caspian Oil represented the least heat-exposed subsector, with its limited operations largely confined to the northern Caspian region, corresponding predominantly to thermoneutral and mild heat-stress classes. Overall, the petroleum sector exhibited a pronounced south-to-north PET exposure gradient, characterized by the predominance of severe and extreme occupational heat stress across upstream production, gas processing, petrochemical manufacturing, and refining activities. Spatial heterogeneity was minimal among the major southern energy industries, whereas northern petroleum operations accounted for the lowest occupational thermal exposure. Coke-making facilities were almost exclusively clustered within regions classified as severe PET-derived

physiological heat stress ( $PET >41$  °C), with only a limited number of facilities occurring in moderate heat stress ( $PET \approx 35$  °C) zones and none located within thermoneutral or cold-stress environments. This spatial configuration delineated a highly homogeneous thermal exposure profile, characterized by minimal spatial heterogeneity and a pronounced concentration within the warmest climatic regions of Iran. Accordingly, the coke-making sector exhibited one of the highest degrees of spatial concordance between industrial infrastructure and severe physiological thermal stress, representing one of the industrial sectors with the greatest potential occupational heat-exposure burden.

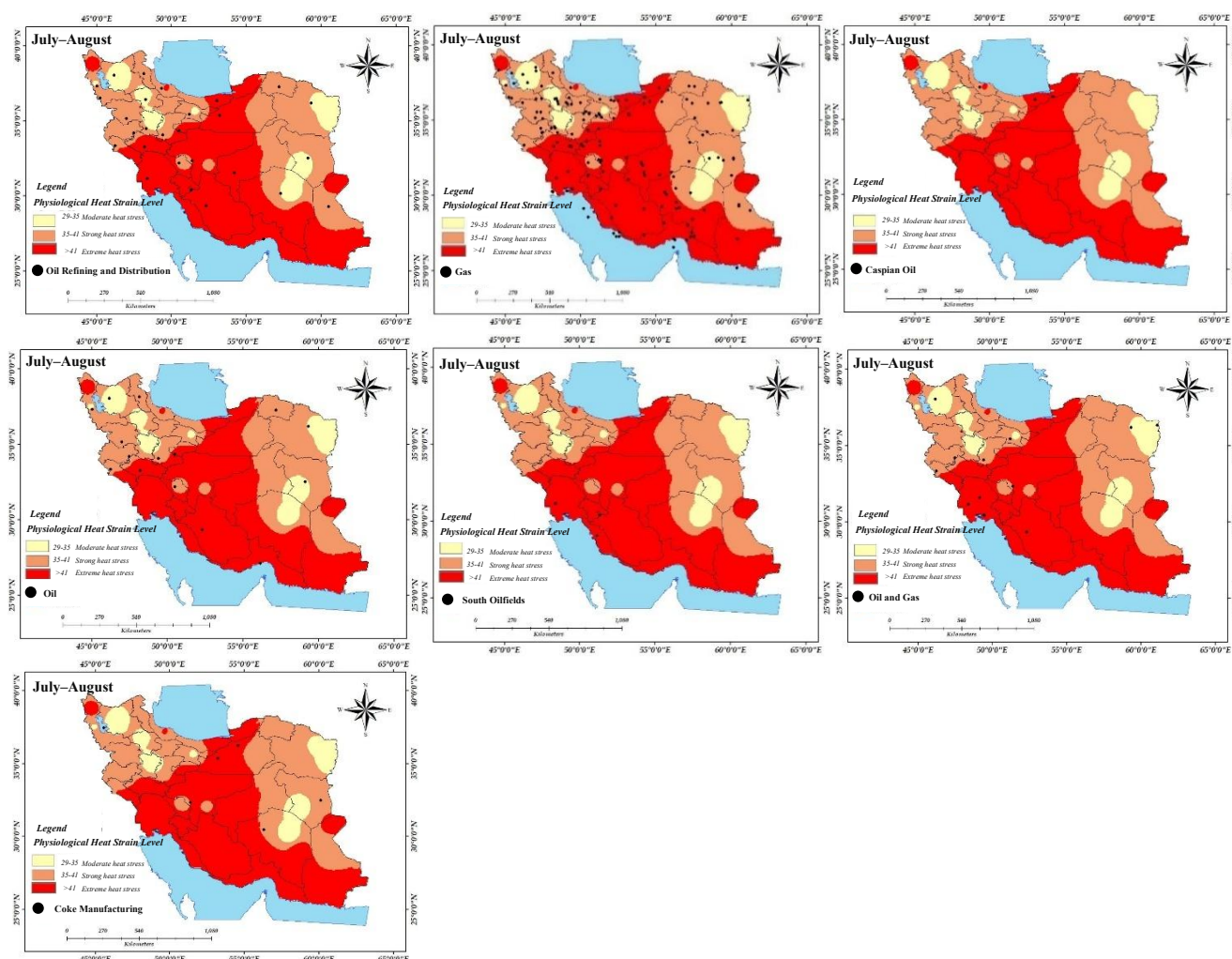


**Fig 6.** Spatial concordance between Oil, Gas, and Petrochemical facilities and PET-derived physiological heat stress classes across Iran during August.

### 3.9. Chemical Industries Across PET-Based Heat Stress Classes

The spatial distribution of the rubber and plastics industry (Fig. 7) exhibited a geographically dispersed pattern across Iran, with facilities predominantly clustered within moderate-to-severe PET-defined heat-stress zones.

Thermoneutral and mild heat-stress conditions were largely restricted to northern and northwestern provinces, whereas facilities exposed to extreme heat stress were confined primarily to the southern industrial corridor and represented only a small fraction of the sector. No facilities occurred within PET-defined cold-stress categories. Relative to the petroleum industry, the rubber and plastics sector demonstrated an intermediate occupational heat-exposure burden, accompanied by greater spatial heterogeneity and a distinct north-to-south transition from thermoneutral environments to predominantly severe heat-stress conditions.

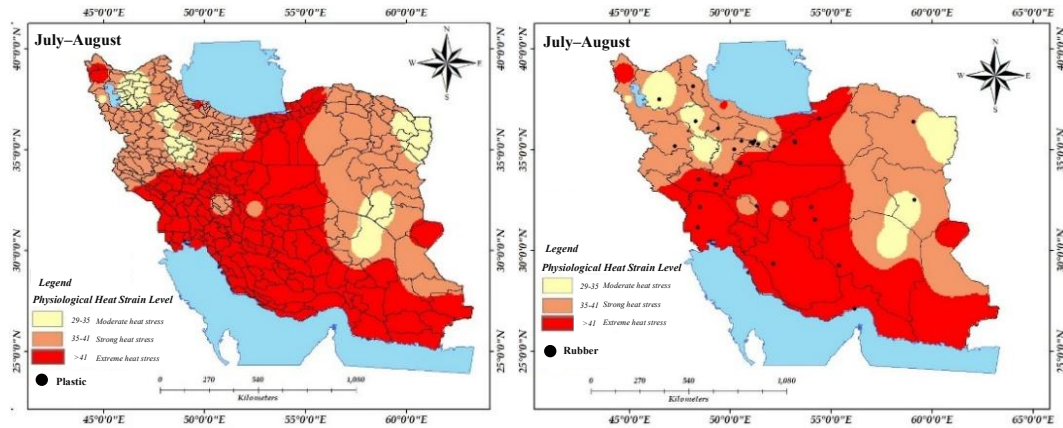


**Fig 7.** Spatial concordance between chemical facilities and PET-derived physiological heat stress classes across Iran during August

### 3.10. Mineral Industries Across PET-Based Heat Stress Classes

Fig.8 depicts marked spatial heterogeneity in PET-defined occupational thermal exposure across the mineral industry. Coal mining exhibited the lowest heat-exposure burden, with most operations located within thermoneutral and mild heat-stress zones in northern and northeastern Iran, and only sporadic facilities situated in severe heat-stress areas. Glass manufacturing, porcelain and ceramics, and metal ore mining demonstrated intermediate exposure profiles, with facilities predominantly concentrated within moderate-to-severe PET heat-stress classes across central and western regions, while relatively few operations occurred under thermoneutral conditions. In contrast, non-metallic ore mining and general mineral extraction exhibited the greatest occupational thermal burden, with the majority of facilities clustered in the central, southern, and southwestern mining corridors corresponding to severe and, locally, extreme PET heat-stress categories. No facilities were located within PET-defined cold-stress classes. Overall, the mineral sector displayed a pronounced north-to-south occupational heat-exposure gradient, with the lowest exposure observed in coal mining, intermediate exposure in glass manufacturing, porcelain and ceramics, and metal ore mining, and the highest exposure in non-metallic ore and general mineral extraction, underscoring substantial spatial heterogeneity in occupational thermal stress.

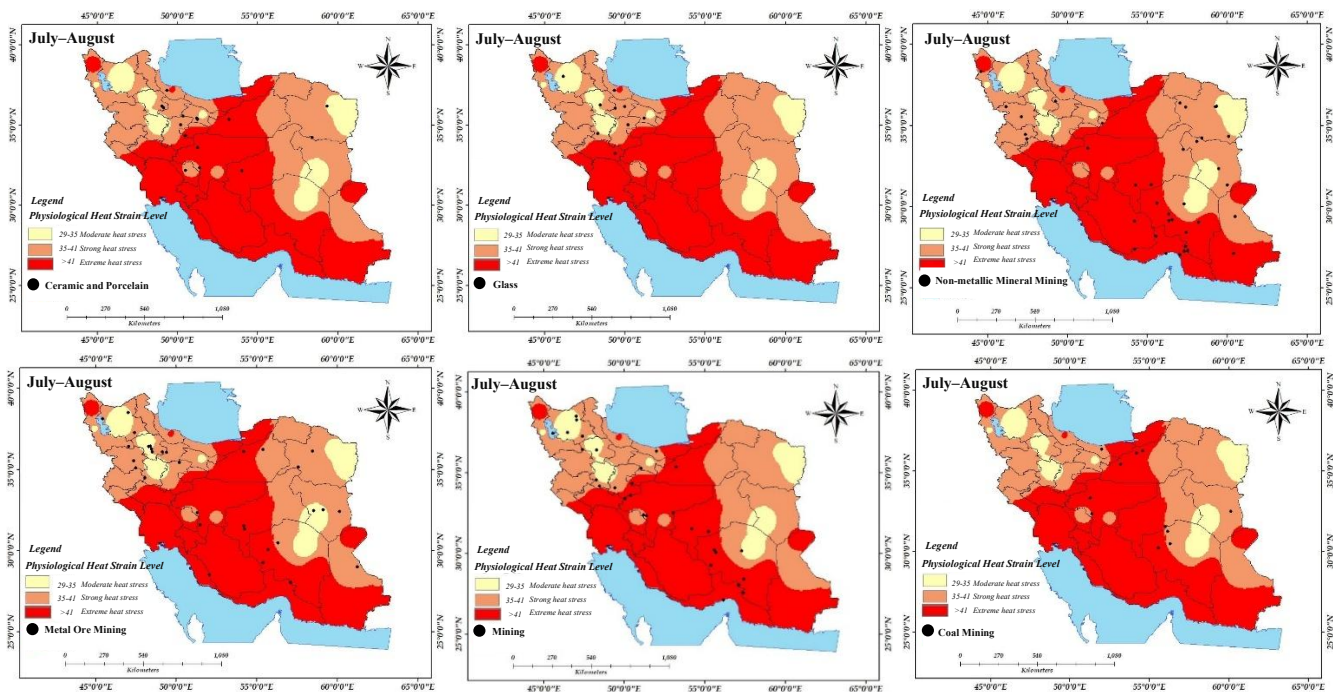


**Fig 8.** Spatial concordance between minerals facilities and PET-derived physiological heat stress classes across Iran during August

### 3.10. Metal and Casting Industries Across PET-Based Heat Stress Classes

As illustrated in Fig. 9, PET-based spatial classification indicated a highly homogeneous thermal exposure pattern across the metal and casting sector during August. Steel, rebar, and sheet–pipe manufacturing facilities were overwhelmingly concentrated within regions classified as severe heat stress (PET >41°C), with only limited establishments located in moderate heat stress (35–41°C) or thermoneutral (18–29°C) zones. The broader metal industry exhibited greater geographic dispersion while maintaining a comparable exposure profile, with the majority of facilities remaining within the severe heat stress belt extending across central, southern, southwestern, and southeastern Iran.

Across all subsectors, cold stress and mild heat stress categories were virtually absent, and thermoneutral exposure accounted for only isolated industrial locations, primarily in the northwestern and northeastern regions. Overall, the sector demonstrated minimal between-subsector heterogeneity, with severe PET-defined physiological heat stress predominating across steel, rebar, sheet–pipe, and general metal industries.

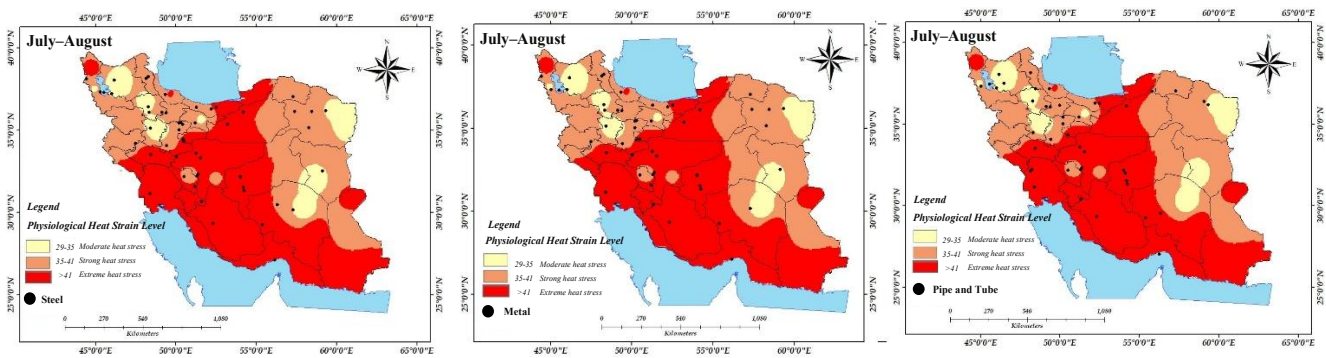


**Fig 9.** Spatial concordance between metal and casting facilities and PET-derived physiological heat stress classes across Iran during August

## 4. Discussion

### 4.1. Overall Interpretation of the National Occupational Heat-Exposure Landscape

Overall, the nationwide integration of long-term PET climatology with the spatial distribution of industrial infrastructure delineates a coherent occupational heat-exposure landscape in which major industrial activities are geographically aligned with regions characterized by persistent severe-to-extreme physiological thermal stress, highlighting substantial spatial concordance between climatic heat hazards and industrial development across Iran (Höppe, 1999). Rather than representing isolated geographical hotspots, the observed exposure pattern suggests that occupational thermal burden is embedded within the broader climatic and industrial geography of the country, where macroclimatic gradients shape the environmental context in which industrial activities are concentrated (Kjellstrom, 2016).

This nationwide exposure configuration expands conventional climatological assessments by characterizing environmental heat from a physiologically meaningful occupational perspective, thereby linking long-term biometeorological conditions with the spatial organization of industrial infrastructure instead of evaluating these components independently (Höppe, 1999). Importantly, the present findings characterize the environmental conditions under which occupational heat exposure is likely to occur rather than directly inferring heat-related morbidity, productivity loss, or physiological impairment, thereby remaining consistent with the ecological design of the study while providing a robust framework for national-scale exposure characterization (Gao et al., 2018). The observed spatial heterogeneity further indicates that occupational heat exposure should be viewed as a geographically structured environmental determinant, with considerable variation in potential thermo-physiological burden according to the spatial coincidence between industrial localization and regional climatic conditions (Kjellstrom, 2016).

## **4.2. Comparison with International Evidence**

The nationwide exposure landscape identified in the present study aligns closely with a growing body of international evidence indicating that climate-sensitive industries are increasingly concentrated within environments experiencing substantial environmental heat loading, particularly across arid and semi-arid regions where rising ambient temperatures amplify occupational thermal exposure (Habibi et al., 2021). Previous investigations conducted among construction workers, miners, agricultural laborers, steel workers, and other outdoor occupational groups across Australia, South Asia, China, and the Middle East consistently demonstrate that prolonged environmental heat exposure represents one of the principal determinants of occupational heat strain, particularly under conditions combining high radiant temperature, elevated humidity, and substantial metabolic workload (Fatima et al., 2021).

Although many previous studies have focused primarily on individual occupations or workplace-specific thermal environments, the present nationwide assessment extends existing evidence by integrating long-term physiological thermal conditions with the spatial distribution of industrial sectors, thereby providing a broader ecological perspective on occupational heat exposure that complements individual-level epidemiological investigations (Gao et al., 2018). The predominance of industrial facilities within severe PET-defined heat-stress environments is likewise compatible with previous biometeorological investigations demonstrating that persistent climatic heat exposure is not randomly distributed but follows distinct geographical gradients associated with regional climate, land use, and industrial development patterns (Matzarakis et al., 1999).

In contrast to studies relying exclusively on WBGT or air temperature, the present analysis incorporates a physiologically based thermal index that captures the combined influence of air temperature, humidity, wind speed, and radiant heat, thereby enabling a more integrated representation of the environmental conditions experienced by occupational populations across diverse climatic regions (Höppe, 1999).

## **4.3. Interpretation of Industrial Spatial Patterns**

The marked spatial concordance between major industrial clusters and regions experiencing severe PET-derived physiological thermal stress appears to reflect the long-standing interaction between industrial localization, climatic suitability, and regional resource distribution rather than a random geographical configuration, resulting in the concentration of industrial infrastructure within environments characterized by persistently elevated environmental heat loading (Calvin et al., 2023; A. D. Flouris et al., 2018; Höppe, 1999). This geographical overlap is consistent with the broader concept of occupational exposure ecology, whereby environmental hazards and workforce distribution converge spatially to create distinct industrial heat-risk landscapes that vary according to regional climatic heterogeneity and patterns of industrial development (Briggs, 2005; Elliott & Wartenberg, 2004).

The relatively homogeneous PET exposure profiles observed across mining, metal-processing, and petrochemical industries further suggest that sector-specific thermal environments are largely determined by the geographical siting of industrial activities within persistently warm climatic zones rather than by localized thermal anomalies alone (A. D. Flouris et al., 2018; Kjellstrom, 2016). Moreover, the predominance of severe physiological thermal stress across geographically dispersed industrial facilities indicates that macroclimatic gradients exert a stronger influence on environmental heat exposure than local-scale spatial variability, reinforcing the importance of incorporating regional climatic context into occupational exposure assessment (Höppe, 1999; Ioannou et al., 2022).

The spatial patterns observed for the agricultural and coke-making sectors further illustrate the heterogeneity of industrial thermal exposure across Iran. Agricultural activities exhibited broad spatial overlap with regions characterized by strong-to-extreme PET-derived physiological heat stress, reflecting the extensive distribution of outdoor production systems across climatically warm regions. In contrast, coke-making facilities were almost exclusively confined to extreme PET classes, delineating a geographically restricted yet highly concentrated thermal exposure profile. Together, these contrasting patterns suggest that sector-specific industrial localization, superimposed on regional climatic gradients, contributes substantially to the spatial configuration of occupational environmental heat exposure across diverse industrial settings (A. D. Flouris et al., 2018; Ioannou et al., 2022; Kjellstrom, 2016).

From a biometeorological perspective, these findings emphasize that environmental heat exposure should not be interpreted solely as a function of ambient air temperature but rather as the cumulative consequence of interacting atmospheric variables, including air temperature, humidity, wind speed, and mean radiant temperature, all of which are integrated within the PET framework to represent human thermo-physiological conditions more realistically (Epstein & Moran, 2006; Höppe, 1999; Matzarakis et al., 1999). The observed spatial clustering therefore extends beyond conventional climatic mapping by delineating an ecologically meaningful thermal exposure landscape in which industrial workforce vulnerability is geographically structured according to the spatial coincidence between industrial infrastructure and long-term physiological heat stress (Calvin et al., 2023; A. D. Flouris et al., 2018).

Nevertheless, these spatial patterns should be interpreted as indicators of environmental heat exposure potential rather than direct measures of occupational heat strain or heat-related health outcomes, as individual physiological responses remain strongly modified by metabolic workload, clothing insulation, work–rest schedules, acclimatization status, hydration practices, engineering controls, and other workplace-specific adaptive factors (Epstein & Moran, 2006; Ioannou et al., 2022; Parsons, 2007). Consequently, integrating long-term PET climatology with industrial geography provides a physiologically grounded and spatially explicit framework for characterizing industrial thermal vulnerability, thereby advancing ecological occupational exposure assessment without extending inference beyond the observational scope of the present study (Calvin et al., 2023; A. D. Flouris et al., 2018; Höppe, 1999).

#### **4.4. Occupational Epidemiology Perspective**

From an occupational epidemiology perspective, the marked spatial convergence of industrial infrastructure with PET-defined severe-to-extreme thermal environments delineates a geographically structured occupational heat burden, characterizing the environmental context of exposure rather than direct health outcomes (Andreas D Flouris et al., 2018; Romanello et al., 2023). This contrast was particularly evident between the geographically extensive agricultural sector and the spatially concentrated coke-making industry, both of which exhibited substantial PET-derived thermal exposure despite markedly different industrial distribution patterns (A. D. Flouris et al., 2018; Romanello et al., 2023). The predominance of mining, metal-processing, petrochemical industries within persistently high-PET regions is consistent with international evidence demonstrating that sustained environmental heat loading substantially increases thermoregulatory demand and cumulative occupational heat exposure, particularly in sectors involving moderate-to-high metabolic workloads and outdoor or semi-outdoor activities (Andreas D Flouris et al., 2018; A. D. Flouris et al., 2018; Ioannou et al., 2022; Morrissey et al., 2021).

Because occupational heat burden is determined by the interaction between environmental heat load, metabolic heat production, clothing insulation, acclimatization, work organization, and engineering controls, comparable climatic conditions do not necessarily translate into equivalent physiological heat strain across industrial settings (Epstein & Moran, 2006; Foster et al., 2020). Accordingly, the widespread spatial overlap between industrial activities and severe PET-defined thermal environments should be interpreted as an indicator of cumulative environmental heat exposure potential rather than direct evidence of occupational heat illness or productivity loss. This distinction is fundamental to ecological occupational epidemiology, where environmental exposure is recognized as a prerequisite but not a surrogate for individual health outcomes (Andreas D Flouris et al., 2018; Ioannou et al., 2022). By integrating long-term PET climatology with industrial geography, the present analysis extends conventional workplace-based heat assessments toward a spatially explicit characterization of industrial thermal vulnerability, providing an ecological framework for evaluating climate-sensitive occupational exposure across heterogeneous industrial landscapes (Andreas D Flouris et al., 2018; Höppe, 1999; Matzarakis et al., 1999).

#### **4.5. Scientific Contribution of PET**

The use of Physiologically Equivalent Temperature (PET) enhances occupational heat exposure assessment by integrating the principal determinants of human heat exchange including air temperature, humidity, wind speed, mean radiant temperature, metabolic heat production, and clothing insulation into a physiologically meaningful index that more comprehensively characterizes environmental heat loading than single-parameter thermal metrics (Höppe, 1999; Matzarakis et al., 1999). Unlike empirical heat indices, PET is grounded in the human energy balance and expresses thermal conditions in physiologically interpretable units, enabling standardized comparisons across heterogeneous climatic settings while improving the ecological characterization of occupational thermal exposure (Höppe, 1999; Walther & Goestchel, 2018).

Although WBGT remains the benchmark for workplace heat management and UTCI is widely applied in biometeorological and public-health research, PET offers distinct advantages for long-term geospatial exposure assessment by explicitly incorporating radiative, aerodynamic, and thermophysiological processes that govern human heat balance (Bröde et al., 2012; Epstein & Moran, 2006). By integrating a 66-year PET climatology with the nationwide distribution of industrial facilities, the present study extends biometeorological applications beyond workplace-scale assessments to a spatially explicit ecological framework that captures long-term thermal exposure landscapes and enables systematic stratification of industrial sectors according to their climatic heat burden (A. D. Flouris et al., 2018). This integration of physiological thermal stress with industrial geography advances occupational biometeorology by providing a robust framework for nationwide industrial thermal vulnerability assessment, bridging climatology, spatial epidemiology, and occupational exposure science while remaining consistent with the ecological scope of the analysis (Kjellstrom, 2016; Romanello et al., 2023).

#### **4.6. Strengths and Limitations**

The principal strength of this study is the integration of a 66-year PET climatology with a nationwide geospatial inventory of industrial facilities, providing, to our knowledge, the first physiologically based characterization of climate-related occupational heat exposure across Iran. Coupling a human-biometeorological index with GIS-enabled industrial mapping extends conventional workplace-scale assessments to a national ecological framework, enabling consistent spatial stratification of industrial thermal vulnerability and comparative evaluation across heterogeneous industrial sectors (Bröde et al., 2012; A. D. Flouris et al., 2018; Höppe, 1999). Furthermore, PET offers a physiologically robust exposure metric by integrating air temperature, humidity, wind speed, and mean radiant temperature within a human energy-balance framework, thereby improving ecological characterization of long-term environmental heat loading (Epstein & Moran, 2006; Matzarakis et al., 1999).

Several limitations warrant consideration. The ecological design precludes inference at the individual worker level; consequently, PET-derived exposure represents environmental heat exposure potential rather than physiological heat strain or heat-related health outcomes (A. D. Flouris et al., 2018). In addition, individual determinants of thermo-physiological response including metabolic workload, clothing insulation, acclimatization, work–rest schedules, hydration status, and engineering controls were not incorporated (Epstein & Moran, 2006; Foster et al., 2021). The industrial inventory was also cross-sectional, and indoor thermal conditions together with local microclimatic variability could not be explicitly resolved. These constraints, however, do not diminish the study's primary contribution as a nationwide ecological assessment of industrial thermal vulnerability and long-term occupational heat exposure patterns.

#### **4.7. Closing Perspective**

Integrating long-term PET climatology with nationwide industrial distribution advances the spatial assessment of climate-related occupational heat exposure by providing a physiologically grounded characterization of industrial thermal vulnerability. This biometeorological–geospatial framework extends ecological exposure assessment beyond conventional workplace-based analyses and strengthens the integration of climatology, industrial geography, and occupational epidemiology. Consequently, the study contributes a scalable methodological framework for national occupational heat-risk characterization and reinforces the role of PET in climate–health research.

#### **5. Conclusion**

This study advances occupational heat exposure science by integrating a 66-year PET climatology with industrial geography to characterize the national spatial distribution of climate-related occupational heat exposure across Iran. The pronounced spatial concordance between industrial infrastructure and persistently elevated PET-derived physiological thermal stress delineates a heterogeneous landscape of industrial workforce vulnerability, demonstrating substantial spatial variability in environmental heat exposure across industrial sectors and climatic regions. Although severe-to-extreme PET-defined thermal environments predominated across mining, metal processing, and most petroleum-related industries, notable sector-specific heterogeneity was evident. Agricultural activities exhibited comparatively greater representation within thermoneutral and lower heat-stress environments, whereas coke manufacturing displayed a distinct thermal exposure profile relative to other petroleum-related industries, underscoring the importance of accounting for intra-sectoral variability when characterizing occupational thermal exposure.

Beyond conventional climate-based assessments, the proposed biometeorological geospatial framework translates long-term physiological thermal conditions into spatially explicit patterns of industrial thermal vulnerability, thereby strengthening ecological occupational exposure assessment and national-scale thermal risk stratification. By integrating biometeorology, industrial geography, spatial epidemiology, and environmental physiology, this framework extends current approaches to characterizing climate-sensitive occupational environments while preserving appropriate ecological inference. As climate change continues to intensify environmental heat exposure, combining physiologically meaningful thermal indices with spatial industrial datasets provides a robust scientific foundation for advancing occupational biometeorology, industrial heat-risk characterization, and climate-health exposure assessment across diverse industrial landscapes.

#### **List of abbreviations**

PET: Physiologically Equivalent Temperature  
MEMI: Munich Energy-balance Model for Individuals  
GIS: Geographic Information System  
IDW: Inverse Distance Weighting  
WBGT: Wet Bulb Globe Temperature  
UTCI: Universal Thermal Climate Index  
VP: Vegetation Proportion  
UI: Urban Index  
HSI: Heat Stress Index

## **Declarations**

### **Ethics approval and consent to participate**

Ethical approval was not required because the study was based exclusively on publicly available environmental and industrial geospatial data and did not involve human participants, biological samples, or identifiable personal information.

### **Consent for publication**

Not applicable.

### **Availability of data and materials**

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

### **Competing interests**

The authors declare that they have no competing interests.

### **Funding**

This research received no external funding.

### **Authors' contributions**

MBK contributed to the study design, data collection and processing, and drafted the manuscript. AD contributed to the study design, data analysis and interpretation, and critically revised the manuscript. SMHS performed the climatological and PET analyses, as well as the spatial and statistical analyses. FG supervised the study,

contributed to the methodological design and interpretation of the findings, and critically revised the manuscript. All authors read and approved the final manuscript.

## Acknowledgements

The authors gratefully acknowledge the Iranian Meteorological Organization for providing long-term climatic observations and all institutions that facilitated access to industrial spatial datasets.

## Declaration of Generative AI

The authors used a generative artificial intelligence tool solely to improve language clarity and grammar. All scientific content, interpretation, data analysis, and conclusions were independently developed, verified, and approved by the authors, who accept full responsibility for the manuscript.

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