

Investigating Outdoor Heat Stress Using Environmental Parameters and Selected Thermal Indices in Northern India



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Abstract Heat stress is often an unacknowledged occupational health hazard especially in developing countries. Climatic zones like tropical and subtropical regions having higher air temperature, humidity and radiant temperature values may impose greater risks of heat-related illness and safety threats to users employed in developing countries having low and medium incomes. Present study aimed at assessing the environmental variables followed by evaluating the heat stress exposures levels at different time periods during the hot summer season utilizing widely used indices, i.e. wet bulb globe temperature (WBGT), discomfort index (DI), humidex (HD), heat index (HI), tropical summer index (TSI); so to have better insights of the stressful thermal climatic conditions experienced by the users engaged in outdoor work activities. Results revealed higher heat stress exposure levels attributable to noon and afternoon periods, indicating stressful climatic conditions, with respective indices exceeding the threshold limit values (TLVs). For WBGT, strong relationship was observed with TSI (R^2 -value = 0.918) and DI (R^2 -value = 0.891) indices, although least association with HI (R^2 -value = 0.644) and HD (R^2 -value = 0.566) indices. However, highest association was observed among HI and HD indices (r -value = 0.995; p -value < 0.01). From results, it may be concluded that noon and afternoon time periods could impose excessive heat strain on user's work capabilities as compared to morning and evening periods, which could cause greater risks of heat-related morbidities and safety threats to workers/users employed, with consequent negative impacts on productivity and financial burden.

Keywords Environmental variables · Negative impacts · Heat stress indices · Exposure assessment

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1 Introduction

India is a diverse country with extreme climatic conditions ranging from tropical to subtropical regions, and there is huge unorganized sector [1]. Climatic zones like tropical and subtropical regions having higher air temperature and humidity values may cause a greater risks of heat-related illness and safety threats to users employed in developing countries having low and medium incomes. In developing countries like India, heat stress is often considered as an ignored occupational health hazard. A prolonged period of heat exposure could affect the production level, and at the same time, it will negatively impact the performance of the user [2]. There are six main agents of thermal comfort (four environmental factors; air temperature, radiant temperature, air speed and relative humidity, and two individual factors; metabolic rate and clothing worn) that accord to the heat stress exposure experienced by the user. Several indices have been developed for the assessment of heat stress exposure, but each varies depending on the considered environmental and personal factors [3]. Previous studies reveal that wet bulb globe temperature (WBGT) index could be used as an optimal heat stress index, due to its applicability under hot work environments [3–6]. But, merely relying on a single index may generate inappropriate results. So, it could also be used in combination with other widely used heat stress indices like discomfort index (DI), humidex (HD), heat index (HI), tropical summer index (TSI), etc., which will provide better detailed estimation of the thermal strain experienced by the targeted audience. According to a previous study in India, during the hot summer season, millions of poor workers are affected by excessive workplace heat with consequent health risks, which ultimately affects their productivity and daily incomes [5]. Ahmed et al. (2020) analysed thermal stress exposure among workers engaged in outdoor construction work activities in UAE, by evaluating the WBGT, HSI and TWL indices for comparative analysis, with WBGT exceeding the threshold limit values (TLVs). The authors suggested that more in-depth analysis can be done using alternative indices in locations where the WBGT index is high [6]. From previous research findings, it is evident that these indices could effectively be used for analysing the heat stress exposure levels under the targeted thermal work ambience. Several assessment studies have been conducted under various work sectors in developed countries, but there is still a lot of research work required to be executed in developing countries. As the geographical conditions differ from one country to another; there is need to explore various environmental factors affecting thermal comfort in a rigorous manner. The present study aimed at assessing the environmental variables followed by evaluating the heat stress exposures levels during the hot summer season utilizing widely used indices, so to have better insights of the stressful thermal climatic conditions experienced by the users engaged in outdoor work activities, followed by descriptive and inferential statistical analysis for the evaluated heat stress parameters. A comparative analysis has also been performed between the summer and winter season under the same geographical location.

2 Methodology

In present study, five different widely used heat stress indices have been considered for evaluating the heat stress exposure level under outdoor climatic conditions during the hot summer season (June–July, 2020) in Chandigarh union territory of India (30° 44' 14 N; 76° 47' 14 E) and additionally during the winter season (January, 2021) also. The environmental measurements were monitored using Kestrel 5400 Heat stress tracker Pro (Nielsen-Kellerman Co.; USA) [7], placed on a tripod at 1.1 m floor surface height as per standards [4]. The equipment was allowed to stabilize for period of 15–20 min, after which the monitored readings were considered for evaluation purposes as shown in Fig. 1.

The environmental variables were monitored during four different time periods throughout the day (i.e. morning: 9.30 A.M. to 10.30 A.M.; noon: 11 A.M. to



Fig. 1 Monitoring heat stress environmental variables at different time periods

12:30 P.M.; afternoon: 1:00 P.M. to 3:30 P.M.; evening: 4:30 P.M. to 6:00 P.M.). From the monitored variables, respective heat stress indices were evaluated to analyse the associated risk exposure levels. Further descriptive and inferential statistics have been performed on the evaluated variables. IBM SPSS Statistics 26 have been used for analysing the evaluated variables; scatterplots and regression lines were plotted for the considered heat stress indices and further Pearson product moment correlation was also performed for analysing the respective associations.

2.1 Considered Heat Stress Indices

2.1.1 Wet Bulb Globe Temperature (WBGT)

WBGT is an empirical index, which is a widely used and validated heat stress index [4], for assessing hot work environments considering the combined effects of air temperature, humidity, air velocity and radiation by measuring natural wet bulb temperature (T_{nw}), dry bulb temperature (T_a) and radiant temperature using Globe temperature (T_g) for both indoor and outdoor work conditions.

$$\text{For indoor work environment : } \mathbf{WBGT} = 0.7T_{nw} + 0.3T_g \quad (1)$$

$$\text{For outdoor environment : } \mathbf{WBGT} = 0.7T_{nw} + 0.2T_g + 0.1T_a \quad (2)$$

2.1.2 Tropical Summer Index (TSI)

TSI is an empirical heat stress index based on the Indian climatic conditions [8]. It gives an equivalent temperature of still air at a constant relative humidity of 50%, which provides the similar thermal sensation experienced by a user as the actual environment under consideration. It is expressed by a mathematical relation involving (T_{wb}) wet bulb temperature ($^{\circ}\text{C}$), (T_g) globe temperature ($^{\circ}\text{C}$), and (V_{ar}) air speed (m/s) as under:

$$\mathbf{TSI} = 0.308 * T_{wb} + 0.745 * T_g - 2.06\sqrt{V_{ar}} + 0.841. \quad (3)$$

2.1.3 Heat Index (HI)

Heat index (HI) involves the use of a regression equation based on two environmental factors, i.e. (RH) relative humidity in per cent and (T_a) air temperature (in degree Fahrenheit) [9]. The developed heat index regression equation was developed by Rothfusz and is given by:

$$\begin{aligned}
\mathbf{HI} = & -42.379 + 2.04901523 * T_a + 10.14333127 * \text{RH} \\
& - 0.22475541 * T_a * \text{RH} - 0.00683783 * T_a^2 \\
& - 0.05481717 * \text{RH}^2 + 0.00122874 * T_a^2 * \text{RH} \\
& + 0.00085282 * T_a * \text{RH}^2 - 0.00000199 * T_a^2 * \text{RH}^2
\end{aligned} \quad (4)$$

2.1.4 Humidex (HD)

Humidex developed by Canadian meteorological service department is a direct index (involving dry bulb temperature (T_{db} in $^{\circ}\text{C}$), vapour pressure (P_a in hPa)) for evaluating, how hot the thermal environment feels to an average person, when combining the effect of heat and humidity (dew point temperature) [10].

$$\mathbf{Humidex} = T_{db} + [0.5555(P_a - 10)] \quad (5)$$

$$\mathbf{P}_a = 6.11 * e^{[5417.7530 * ((1/273.16) - (1/T_{dp} \text{ in Kelvin}))]} \quad (6)$$

2.1.5 Discomfort Index (DI)

The development of a direct indices tool called the “discomfort index” based on (T_{wb}) wet bulb temperature (in $^{\circ}\text{C}$) and (T_{db}) dry bulb temperature (in $^{\circ}\text{C}$) with some correction factor, which relates the thermal degree of discomfort perceived by the user in a work environment [11].

$$\mathbf{DI} = 0.5(T_{db} + T_{wb}) \quad (7)$$

3 Results and Discussions

3.1 Environmental Variables

The monitored variables during different time periods (relative humidity, dry bulb temperature, globe temperature, wind speed, natural wet bulb temperature) were further analysed using statistical analysis to draw logical conclusions. During the hot summer season, it was observed that RH values rise during the evening and morning periods as compared to pre-noon and afternoon time periods. Highest values of globe temperature (50.35°C), dry-bulb/air temperature (37.61°C) and air velocity (1.528 m/s) were observed during afternoon period followed by pre-noon period, indicating harsh climatic conditions. Although higher values of natural wet bulb temperature were found during the pre-noon period (31.05°C) followed by afternoon

Table 1 Average values for summer outdoor environmental parameters (mean (SD))

Parameters	Relative humidity (%)	Air temperature (in Celsius)	Globe temp. (in Celsius)	Air velocity (in m/s)	Natural wet bulb temp. (in Celsius)
<i>Day period</i>					
Morning	63.26 (4.563)	29.59 (1.668)	41.34 (2.716)	0.462 (0.465)	26.24 (0.944)
Pre-noon	58.91 (2.225)	35.73 (0.769)	47.99 (1.987)	1.134 (0.727)	31.05 (0.469)
Afternoon	42.31 (2.095)	37.61 (0.641)	50.35 (1.648)	1.528 (0.867)	29.24 (0.424)
Evening	68.08 (3.432)	31.72 (0.895)	33.49 (2.770)	0.643 (0.463)	27.04 (0.653)

Table 2 Range values for outdoor environmental parameters (summer)

Parameters	Relative humidity (%)	Air temperature (in Celsius)	Globe temp. (in Celsius)	Air velocity (in m/s)	Natural wet bulb temp. (in Celsius)
<i>Day period</i>					
Morning	52.5–71.9	26.6–34	35.4–47.3	0–2.3	22.7–28.5
Pre-noon	54.2–65.8	34.1–37.3	39.1–50.7	0–3.8	29.7–31.8
Afternoon	38–50.4	36–39.8	42.6–52.8	0–6.1	27.4–30.4
Evening	62.6–79.8	30.3–34.2	29.9–39.1	0–2.4	26.3–29

(29.24 °C), evening (27.04 °C), and morning (26.24 °C) period as described in Tables 1 and 2 depicts the range values for outdoor environmental variables during summer season. Similar trend was observed with respect to variations among the environmental variables throughout the day during winter season also; however, monitored values (as depicted in Tables 3 and 4) were significantly lower than the summer, as expected.

3.2 Heat Stress Indices

From the analysed variables, considered heat stress indices (i.e. WBGT, HD, HI, DI, TSI) were evaluated as shown in Tables 5 and 6. During summer season, higher heat stress exposure levels were accountable to the noon and afternoon time periods as compared to morning and evening time periods indicating stressful climatic conditions; exceeding the threshold limit values (TLVs). Figure 2 depicts the bar-graphs, comparing evaluated heat stress indices mean values during the summer and winter seasons. Results revealed that respective heat stress indices were exceeding the TLVs during the summer season, indicating hot stressful climatic conditions, which could cause greater risks of heat-related morbidities and safety threats to workers/users employed with consequent negative impacts on productivity and financial burden. Figures 3 and 4 show the variation among evaluated indices (average values) during different time periods throughout the day with respect to summer and winter seasons

Table 3 Average values for winter outdoor environmental parameters (mean (SD))

Parameters	Relative humidity (%)	Air temperature (in Celsius)	Globe temp. (in Celsius)	Air velocity (in m/s)	Natural wet bulb temp. (in Celsius)	Dew point temp. (in Celsius)
<i>Day period</i>						
Morning	84.93 (4.363)	12.78 (1.304)	21.64 (4.067)	0.97 (0.595)	13.01 (1.328)	10.29 (0.661)
Pre-noon	70.24 (3.171)	16.78 (0.894)	25.93 (0.858)	1.22 (0.813)	15.39 (0.473)	11.32 (0.337)
Afternoon	60.71 (1.587)	18.60 (0.427)	26.07 (0.847)	1.38 (0.918)	15.54 (0.287)	10.86 (0.366)
Evening	92.57 (1.657)	9.88 (0.392)	10.20 (0.382)	0.47 (0.456)	9.10 (0.220)	8.73 (0.166)

Table 4 Range values for outdoor environmental parameters (winter)

Parameters	Relative humidity (%)	Air temperature (in Celsius)	Globe temp. (in Celsius)	Air velocity (in m/s)	Natural wet bulb temp. (in Celsius)	Dew point temp. (in Celsius)
<i>Day period</i>						
Morning	73.8–92.3	10.7–16.4	16.5–27.6	0–3.9	11.3–15.2	9.1–12.3
Pre-noon	64.3–77	14.4–18.7	23.5–27.5	0–4.9	14–16.2	10.3–12.2
Afternoon	55.3–65.8	17.3–20.4	24.5–28.1	0–7.8	14.8– 16.2	9.7–12.1
Evening	89.4–95.7	9.1–10.8	9.7–11.4	0–2.9	8.7–9.6	8.2– 9.4

Table 5 Evaluated heat stress indices during the summer season

Indices→	WBGT	HI	HD	DI	TSI
<i>Day period↓</i>					
Morning	29.46 (1.2678)	33.39 (2.9307)	38.62 (2.3291)	27.91 (1.1795)	36.57 (2.4052)
Pre-noon	34.82 (0.7628)	47.87 (1.774)	49.53 (1.2185)	33.40 (0.51133)	42.47 (1.7413)
Afternoon	34.22 (0.5939)	45.09 (1.2509)	47.36 (0.9937)	33.42 (0.3870)	43.39 (1.3735)
Evening	28.83 (1.1665)	39.73 (1.7578)	43.99 (1.1398)	29.38 (0.7076)	30.79 (2.2323)
Overall	31.56 (2.8474)	41.63 (4.8125)	45.02 (3.5156)	31.09 (2.3766)	37.57 (6.0240)

Table 6 Evaluated heat stress indices during the winter season

Indices→	WBGT	HI	HD	DI	TSI
<i>Day period↓</i>					
Morning	14.64 (1.825)	12.73 (1.171)	14.13 (1.582)	12.90 (1.263)	17.39 (3.463)
Pre-noon	17.59 (0.5708)	16.04 (0.7389)	18.62 (1.0114)	16.09 (0.6424)	21.15 (0.8476)
Afternoon	17.90 (0.3578)	17.44 (0.5082)	20.21 (0.5352)	17.07 (0.2506)	21.20 (0.8645)
Evening	9.40 (0.2470)	10.06 (0.3568)	10.53 (0.4526)	9.49 (0.2931)	8.08 (0.4831)
Overall	15.45 (3.423)	14.72 (3.017)	16.71 (3.965)	14.50 (3.044)	17.74 (5.394)

separately, with highest values observed during noon and afternoon session. From results, it may be concluded that noon and afternoon time periods could impose excessive heat strain on user’s work capabilities as compared to the evening and morning work periods. During summer season, for noon and afternoon periods; WBGT values exceeded the TLVs; humidex indicated dangerous discomfort experienced; HI classified the risk category as danger zone, with more chances of heat cramps, heat exhaustion and possible heat cramps with prolonged work activity; TSI also exceeding the TLVs, and DI indicating serious discomfort observed during the respective work periods. However, morning and evening periods were slightly less distressing in terms of thermal ambience as compared to harsh noon and afternoon periods during the summer season.

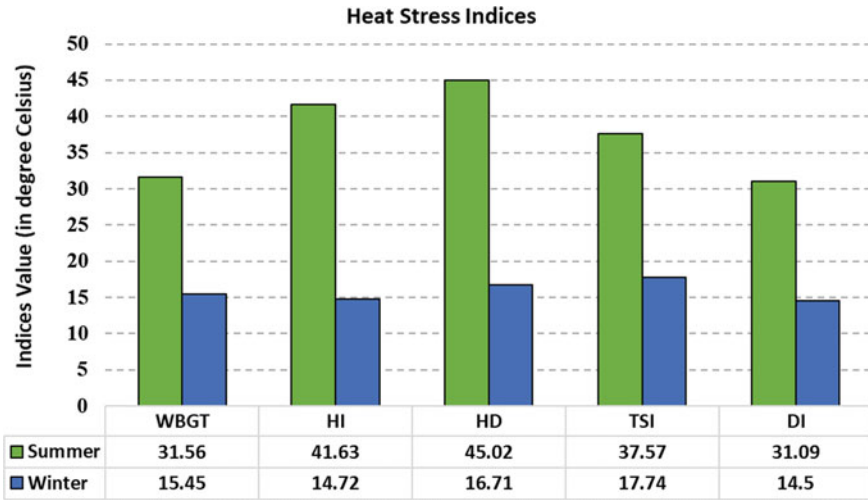


Fig. 2 Variations among considered indices between two different seasons

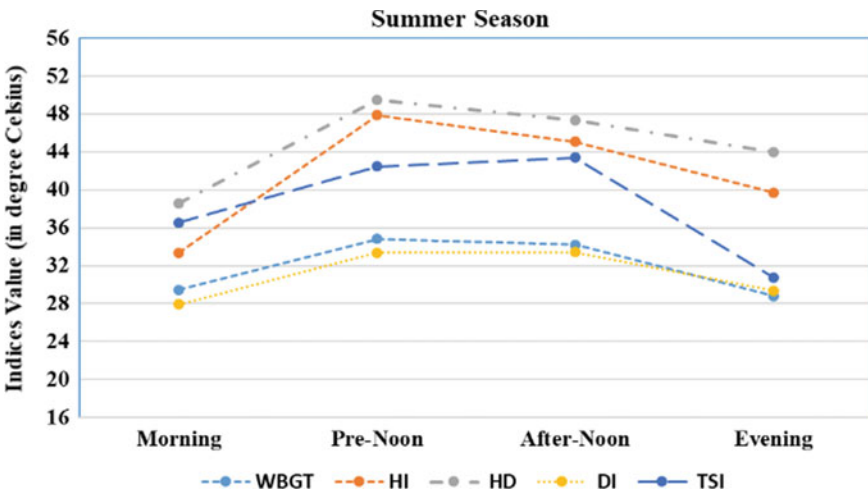


Fig. 3 Indices mean values during different time periods (summer)

3.3 Scatterplots and Correlation Analysis

Further, Pearson product moment correlation was performed using IBM SPSS 26.0 software package for the evaluated heat stress indices. Highest association was observed among HI and HD indices (r -value = 0.995; p -value < 0.01); for WBGT, highest correlation was observed with TSI (r -value = 0.958) and DI (r -value = 0.944), whereas lowest association was found for TSI with HD (r -value = 0.581)

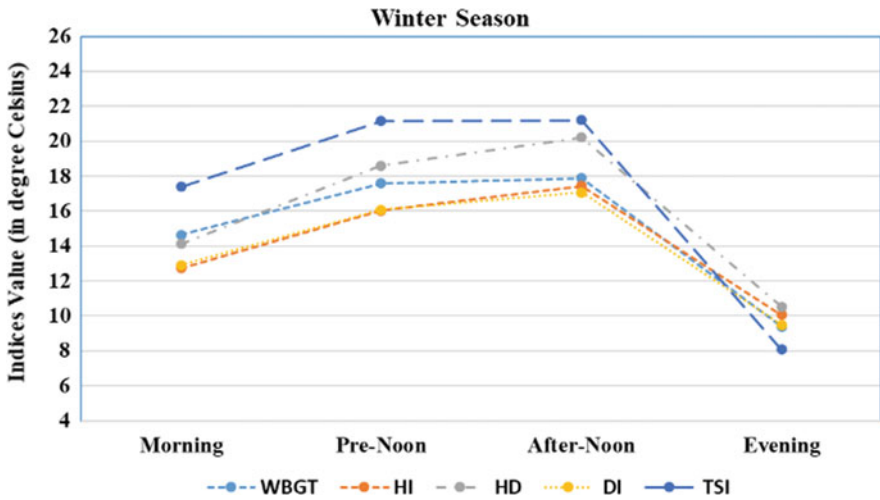


Fig. 4 Indices mean values during different time periods (winter)

and HI (r -value = 0.647) indices (as shown in Table 7). During winter, correlation analysis signified slight variations among the respective heat stress indices (Table 8) as compared to summer results; for WBGT, highest positive association was observed with TSI (r -value = 0.989) and DI (r -value = 0.980); however, strong

Table 7 Bivariate correlation analysis for considered indices (summer period)

	WBGT	HI	DI	TSI	Humidex
WBGT	1	0.803**	0.944**	0.958**	0.752**
HI	0.803**	1	0.935**	0.647**	0.995**
DI	0.944**	0.935**	1	0.850**	0.905**
TSI	0.958**	0.647**	0.850**	1	0.581**
Humidex	0.752**	0.995**	0.905**	0.581**	1

** Correlation is significant at the 0.01 level (2-tailed)

Table 8 Bivariate correlation analysis for considered indices (winter period)

	WBGT	HI	DI	TSI	Humidex
WBGT	1	0.947**	0.980**	0.989**	0.953**
HI	0.947**	1	0.991**	0.915**	0.999**
DI	0.980**	0.991**	1	0.953**	0.994**
TSI	0.989**	0.915**	0.953**	1	0.921**
Humidex	0.953**	0.999**	0.994**	0.921**	1

** Correlation is significant at the 0.01 level (2-tailed)

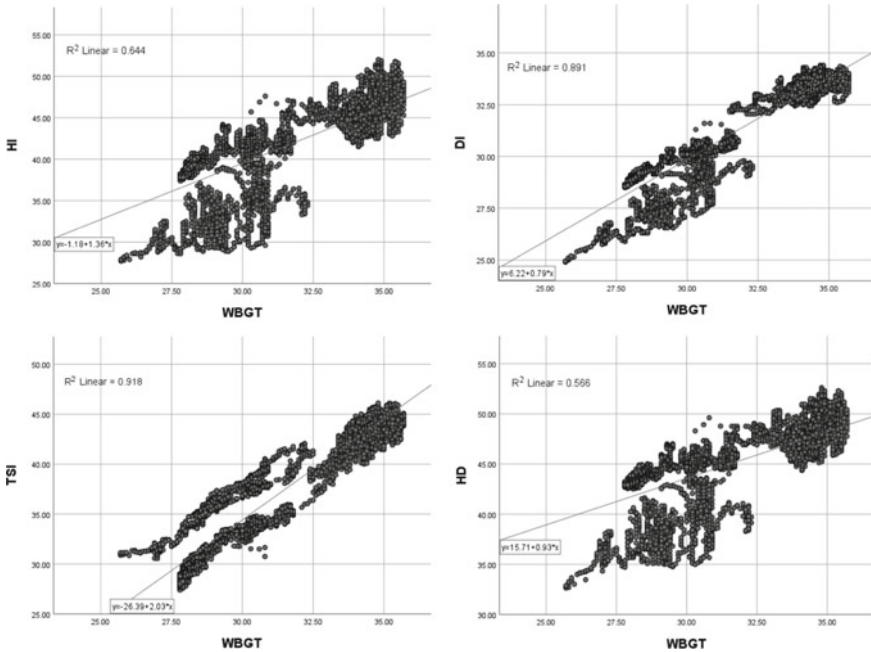


Fig. 5 Scatterplot and regression lines depicting relationship between WBGT and other respective indices

positive relationship was found between HI and HD (r -value = 0.999). Figure 5 depicts the scatterplots and regression lines for the relationship among WBGT and other respective indices, i.e. HI, DI, TSI, HD.

From results, strong relationship was observed among WBGT and TSI (R^2 -value = 0.918); WBGT and DI (R^2 -value = 0.891) indices. Although least association was observed among WBGT and HD (R^2 -value = 0.566); WBGT and HI (R^2 -value = 0.644). From analysed results; it may be concluded that noon and afternoon time periods were prone to stressful thermal conditions, with respective heat stress indices exceeding the TLVs. Remedial control measures could be considered beneficial in improving the thermal ambience, which may include adequate prevention control policies, work-rest periods, regular fluid intake, and even simulation-based control studies; also, engineering control design interventions may be taken as an effective and important control measure in reducing the exposure levels up to the desired permissible limits [12–14].

4 Conclusion

During hot summer season, it was observed that RH values rise during the evening and morning periods as compared to pre-noon and afternoon time periods. Highest

values of globe temperature, dry bulb temperature were observed during afternoon and noon period, indicating harsh climatic conditions. Variations were observed among respective heat stress parameters during different time periods throughout the day. Strong positive association was observed for WBGT, with TSI and DI indices, whereas lowest association was found for TSI with HD and HI indices. Scatterplot and regression lines also showed better relationship among WBGT and TSI, DI indices, however least with HD and HI, but strong relationship was observed between HD and HI. Results indicated that WBGT index could effectively be used in conjunction with other widely used heat stress indices like DI, TSI, which may provide better estimation of the harsh thermal work conditions. Higher exposure levels were accountable to noon and afternoon time periods as compared to morning and evening periods, with respective heat stress indices exceeding the threshold limit values during the summer season, indicating hot stressful climatic conditions, which could cause greater risks of heat-related morbidities and safety threats to users' employed.

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