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ORIGINAL ARTICLE

Limitations of WBGT Index for Application in Industries: A Systematic Review

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ABSTRACT

The Wet Bulb Globe Temperature (WBGT) is still widely applied as a preliminary tool for evaluating heat stress. This index faces some limitations not considered yet. This systematic review was conducted aiming at highlighting some limitations for the development of the WBGT index. The present study was organized using more extensive databases, including PubMed, Google Scholar, Scientific Information Databases (SID), Elsevier, Web of Science, Scopus, Irandoc, Magiran, and Iran Medex. The used search terms were WBGT index, Heat stress, Thermal Stress, Heat strain, Wet Bulb Globe Temperature, Hot Condition, Occupational Health, and Occupational Exposure indices. In this study, 69 articles from the years 1950 to December 2021 were assessed. The WBGT index, despite having some advantages, suffers limitations that should be considered for a more accurate estimate of thermal stress. This study was pointed to the new limitations, including the value of WBGT is not clear for persons whose working in a seated posture. The additional problem with the use of this index was that it was used for adapted people who have consumed enough water and salt, while neither water nor salt is always readily available in most hot working environments. Therefore, using this index will cause an error. Also, in heterogeneous environments, if the heat source is near the head or legs, a coefficient will not be applied to these regions. The results of the study demonstrated that, because of the limitations of the WBGT index, it is recommended that this index be used along with other indicators and physiological parameters to assess heat stress until more extensive studies would be conducted in an attempt to improve and remove its limitations.

KEYWORDS: *Exposure to heat, Heat stress, Thermal stress, WBGT index*

INTRODUCTION

The advancement of technology in societies, on one hand, has increased human convenience and on the other hand, has created problems for people due to the exposure to heat in the living and working environments. An increase in the ambient temperature due to the increased greenhouse gases is one of the impacts of climate change which exposes many people to heat stress [1-2]. It is highly important, because a large number of workers are working in outdoor environments and hot industries, and they have direct exposure to the heat. Exposure to heat stress can pose a variety of heat-related problems such as heat syncope, heat exhaustion, heat cramps, heat shock, confusion, poor concentration, and fatigue. These also might impose costs such as loss of production, loss of workers' income, and increased social expenses [3]. Workers in different industrial environments (indoor or outdoor) can be exposed to high temperatures. They are also exposed to outdoor temperatures and solar heat load in the industries such as agriculture, forestry, fisheries, and construction [4-5]. In naturally ventilated buildings such as iron and steel plants and metallurgy plants, high indoor temperature and strong radiation may adversely affect the workers' health, safety, and productivity [6-7]. The workers are also affected in the hot indoor environments without air-conditioning such as manufacturing industries, smelting plants, bakeries, laundries, and restaurant kitchens [4-5-8].

The increased risk of heat-related illnesses and injuries to the workers has been studied in numerous indoor and outdoor environments [9]. Since 1905, many efforts have been made to measure the thermal stress levels in the workplace or estimate the thermal stress [4-10-25]. To evaluate the heat stress in the workplace, two international standards of ISO (International Organization for Standardization), including 7933 and 9886 were developed. Different heat stress indices for assessing the heat stress in the workplaces have been defined so far [26] one of which is the Wet Bulb Globe Temperature (WBGT) developed by the U.S. Army and Marine Corps in 1950s [27]. It can assess the effects of heat exposure in a period of time for a specific activity and is one of the easiest and most proper heat assessment indices.

The researchers have widely preferred the WBGT index to other indices [28-29]. The WBGT index as one of the highly efficient methods is considered the simplest and most appropriate method for evaluating the environment heat conditions [30]. Parameters such as the ambient temperature, relative humidity (RH), and radiant heat for the outdoor conditions define the WBGT [31]. In calculating the WBGT index, the important environmental factors are dry temperature, wet temperature, mean radiation temperature, and airflow flow rate [32-33]. The factors including clothing, rate of metabolism, and adaptation status were also applied as the correction coefficients in the interpretation of the index [34]. The occupational exposure limits are based on the WBGT so that most workers can tolerate the heat stress for the long term [35]. The sensitivity to the radiant heat and airflow, as the two essential elements in determining the ambient air temperature, are considered by the WBGT index. Despite the advantages of the WBGT index, there are limitations to this index [1].

Since this index is known as one of the most widely used indicators for investigating the thermal stresses in industries, it is necessary to conduct more studies on all aspects of this index.

In this study, we aimed to investigate the limitations of the WBGT index so that everyone, especially specialists and researchers, can get a better understanding of this index and how to use it in various environmental and industrial conditions, by evaluating the factors and variables that affect it. Although some limitations of the index have been stated in previous studies, the novelty of the study was that it highlights the unchecked limitations of the WBGT index after researching studies of heat stress in different countries. The WBGT serves as a reference index for evaluating heat stress at work. Thus, we hope that this study will uncover other imperfections of the index to suggest mixing it with other indexes to improve its performance.

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METHODS

Search Strategy:

We conducted a systematic review of the published studies in the field of the WBGT index in March 2021. This review was organized using more extensive databases including PubMed, Google Scholar, Scientific Information Databases (SID), Elsevier, Web of Science, Scopus, Irandoc, Magiran, and Iran Medex. The search protocol was designed using mainly advised methods as well as PRISMA protocol. The search strategy involved a combination of several keywords related to the field of research, including WBGT index, Heat stress, Thermal stress, Heat strain, Wet Bulb Globe Temperature, Hot Condition, Occupational Health, and Occupational Exposure indexes.

Inclusion and Exclusion Criteria:

Studies deemed eligible for this review were those published in English in internationally peer-reviewed journals and those published in Persian and English languages in Iran. The eligibility of studies was based on the relevance to the application of the WBGT index in workplaces, occupational health, and industries.

According to the PRISMA statement, unrelated articles were excluded. Finally, the related articles were assessed. PRISMA is design guidance that develops and enhances the reporting of structured and meta-analysis reviews. Therefore, the authors of scientific articles use PRISMA's guidelines to prepare and publish a systematic review. Titles, abstracts, and keywords of all the collected articles were carefully reviewed. Therefore, those unrelated to the main purpose of this study were excluded including the studies related to the application of the WBGT index in sports and climate and also the articles mentioned only measured the WBGT index and the articles on the relationship between heat stress and the WBGT index without mentioning the limitations and other fields.

Study selection and data extraction:

All potentially relevant studies were assessed and screened for eligibility by two researchers independently. Almost all WBGT related found studies were considered. 1506 articles were excluded from the study due to the review of title and abstract, irrelevance to the study, and the lack of access to full-text. Finally, 69 full-text articles from the years 1950 to December 2020 were assessed based on the purpose of the study. All review articles, original articles, editorials, and letters to the editor were also reviewed. We found a review article [36] in 2008 focusing on the limitations and history of the WBGT index in all domains. We discussed the other limitations of the WBGT index for use in industries. We also criticized the occupational exposure limits (OEL) to heat assessment in Iran. Figure 1 illustrates the selected studies for this systematic review.

Assessment of Methodological Quality:

In case of any doubt in the study findings, the articles selected for the retrieval were assessed by two independent reviewers in terms of the methodological validity before inclusion in the review. So, an agreement was made among the authors on what could be excluded from the study. Almost all the WBGTs related found studies were considered. Figure 1 provides an overview of the inclusion and exclusion criteria.

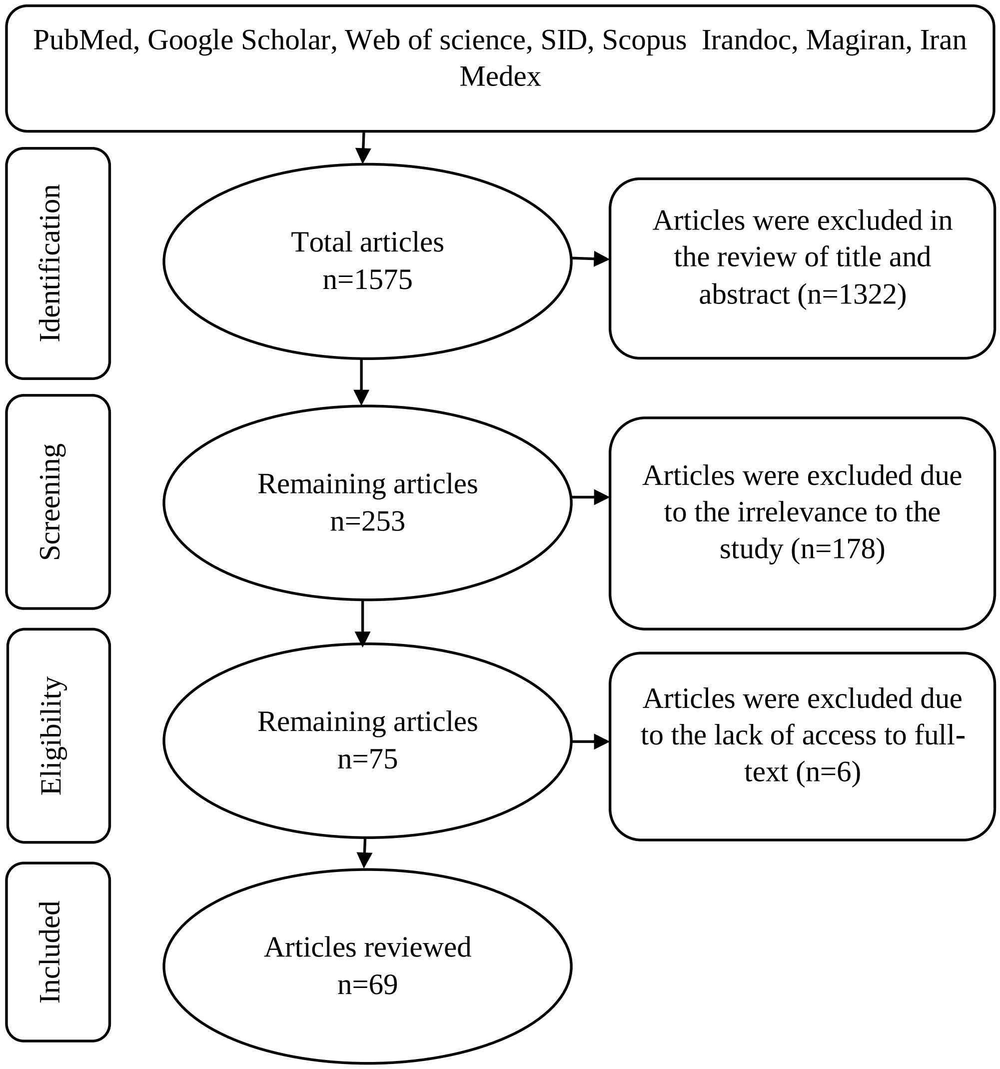

Fig 1. Flow diagram of selected articles.

RESULTS

The results of this study were reviewed as per the relation between the WBGT and other components.

WBGT index and heat stress:

Different studies have been conducted on the different indices of heat stress where the WBGT index was recognized as the appropriate index for the fast assessment of the environmental weather conditions compared to other indices. The major characteristics of the WBGT index are the integration of four basic environmental parameters (i.e. air temperature, humidity, velocity, and radiation) and the lack of separate air velocity measurement (being difficult and costly)[37]. The values obtained from this index can be easily interpreted by users [38]. It is reliable, valid, and feasible as a simple index for monitoring and assessment of warm environments [39]. Since the WBGT can be easily and quickly measured by devices, many standards have suggested this index to evaluate the warm indoor environment with natural ventilation [40-42].

By making a comparison to the other indices of heat stress, the study conducted by Nasiri et al., showed that the WBGT index solely or along with other indices had been used in more than 60 studies on the heat stress assessment [43]. Brake in the year 2002 conducted a study to compare the various indices for determining heat stress to identify the best indices for recognizing heat stress. The results showed that there was a significant difference between the permissible values of various indices, but the WBGT index was an appropriate index to determine heat stress [44]. In recent years, various studies have been published as a confirmation that despite its simplicity, the WBGT index has been still introduced as a reliable index [45-47]. In Golmohammadi et al., study it was also found that the WBGT index is more appropriate to determine heat stress [48].

However, in Canada, the use of this index has been restricted, due to the WBGT work/rest tables based on ACGIH standard (Table1) limitation on determining values above 30°C. On the other hand, whenever a worker uses the cool liquids or is cooled locally, the amount of WBGT was not different from the heat stress condition and both stress conditions showed the same results. So that in a study conducted by Brake et al., (2002) entitled "Deep body core temperatures in industrial workers under thermal stress" on 36 industrial workers, it was found that workers regularly exceeded commonly-recommended limits for industrial hyperthermia (38°C) in terms of maximum deep body core temperature (38.3 ±0.4°C), with no symptoms of heat illness [49]. Therefore, the work/rest schedule (75% - 25%) planned for the workers, regarding the different heat loads, was not desirable [50]. Also in these tables [54], the unmodified WBGT index by default considered the workers' work clothes light [51] and is for someone who has not previously had a bodily injury or illness resulting from an accident and now is healthy [52].

Hajizadeh et al., evaluated the heat stress among the workers of brick-manufacturing units in Qom city based on the WBGT index as well as the relationship between the WBGT and physiological indicators. They concluded that the workers had been exposed to varying amounts of heat stress, depending on the type of work environment (outdoor and indoor). The mean of this index was calculated according to the type of work and WBGT index in outdoor and indoor which were significantly different ($P < 0.05$) (Table 1) [53]. According to Mirzabeigi's recommendation, the WBGT heat stress approach doesn't assess how comfortable an interior environment is for its occupants. Thus, in future studies, an integrated approach to evaluating thermal comfort in conjunction with heat stress conditions would be necessary [54].

Table 1. Mean, SD, min and max of WBGT index (outdoor and indoor) [53]

Environment	WBGT (°C)			
	Mean	SD	Max	Min
Outdoor	26.42	1.31	32.29	23.81
Indoor	32	2.8	37.36	26.36

A) WBGT and Environmental Conditions Parameters:

The WBGT index is a coherent global index for the heat stress assessment in diverse climatic conditions which has not been widely accepted [43]. Despite the advantages mentioned in the previous sections for the WBGT index, some limitations have made its use doubtful. In a glimpse, the following limitations can be considered for this index. The WBGT index is unacceptable in various weather conditions such as air-dry temperature, high humidity, and low wind velocity [55]. Regarding the effectiveness of non-environmental parameters such as activity intensity, work clothing type, and clothing thermal insulation, personal protective equipment, age, and body mass index [56], it does not support the work/rest schedule recommended by ACGIH of the temperatures above 30◦C [49] and different heat load [50-52]. It also does not calculate the direct impact of air velocity on WBGT and as a result, there was little sensitivity to the cooling effects of airflow velocity on the level of heat stresses [57-58]. A review article by Budd (2008) showed the limitation of the WBGT index in evaluating the stress level when sweating is limited rather than when released [36].

The WBGT was also unable to exactly show the additional stress of people when sweat evaporates at high humidity and low movement [36]. In a review study, Francesca et al., explained an experience that everyone in conditions C3 and C4 (40°C or more) feels very hot temperature, but the WBGT value remain numerically quite low (30.6 and 34.1), and many workers and employers and even OH practitioner conclude based on the WBGT value. Conditions C3 and C4 were not considered hot (Table2) [59]. This means that despite the low value of the index, if the amount of the environmental parameters such as air temperature, globe temperature, relative humidity, and wet bulb temperature were high, then these conditions were difficult for people to tolerate. But the calculated WBGT value was low indicating that the ambient temperature conditions were normal.

Table 2. *Typical WBGT values under hot stress conditions* [59]

Condition	Air temp. ta (°C)	Globe Temp Tg (°C)	Air velocity va (m s^{-1})	Relative humidity RH (%)	Partial vapor pressure pa (kPa)	Natural wet bulb Temp Tnw (°C)	WBGT
C1	30	30	0.5	35	1.5	19.4	22.6
C2	35	35	0.5	35	2	23.1	26.7
C3	40	40	0.5	34	2.5	26.6	30.6
C4	45	45	0.5	31	3	29.5	34.1

Although OSHA and ISO were considered the air velocity value for determining the WBGT limits (see Table 3), the problem with the WBGT index's use in different workplaces was that the airflow velocity parameter was determined indirectly. In calculating this index (wet bulb temperature), the most effective parameters were wet and radiation temperatures and the air velocity interferes indirectly. The temperature used as the ball temperature for measuring the amount of radiant heat load in the WBGT index depends on the ambient temperature and airflow velocity. As the air velocity increases and the air temperature decreases, the bulb temperature will further increase. If the air temperature was higher than the skin temperature, the measured bulb temperature will be lower than the real value. Thus, if the air velocity was low, the bulb temperature was higher than the real value [54].

As a result, the WBGT index has little sensitivity to the cooling effect of airflow velocity on the number of heat stresses, and because of possible errors in estimating the effective parameters of this index in different work environments, the results obtained using the WBGT index were generally more conservative [55-56] and as a weak and very cautious index, it was not practical in many situations [62-63].

Undoubtedly, the WBGT outperforms only in measuring the air temperature and humidity, but it measures and responds insufficiently to the humidity and air movement, and thus underrates the stress of restricted evaporation [36]. Therefore, it continues the proven contradiction of effective temperature (ET) and also causes them to get worse for two reasons:

a) WB weight of WBGT was fixed on 0.7; i.e. high in low temperature and insufficient in high temperature [60], but in ET, this weight increases with an increase in the temperature [36].
b) Response of WBGT to the air movement was insufficient; as in low wind velocity, the physiological and subjective strains will disproportionately be high in hot environments [6-36].

For example, a study showed that the clothed men who were alternately exercising and resting for 4 hours in hot-humid conditions endured 'with ease' in wind velocity of 0.8 m/s but when the experiment was repeated with wind velocity 0.1 m/s they could not withstand [61]. The evaporative capacity of the air (Emax) had decreased to one-third of its previous value with a reduction in wind speed [36]. According to industrial experience, the WBGT like ET underrates the strain by the restricted evaporation [36]. Therefore it was suggested to create separate limits of WBGT for air velocity more and less than 300 ft./min (1.6 m/s) [62].

Indoor WBGT is not a function of indoor hot environmental variables so that the index for assessing the heat stress inside and outside the buildings without solar load considers both parameters, i.e. the natural wet bulb temperature (tw), and the bulb globe temperature (tg), but the index was calculated by the addition of aforesaid parameters and also the air temperature (ta). The contribution of each one of the parameters tw was constant, but tg was different for solar and non-solar load environments. Therefore, it may be difficult for the architects to apply the indoor WBGT to determine the admissible indoor thermal conditions during the design phase of naturally ventilated buildings [63]. Thus, it can be seen as a limitation of the WBGT index.

In 2012, a study was conducted in the United States as an experimental approach on the more radiative temperature in the outdoor using the meteorological data. It was concluded that the meteorological data can be used in a variety of ways to predict WBGT in the outdoor, and estimation of WBGT using the meteorological data will have a reliability of 95% [64].

In the study of Konak et al., the authors stated that all indices suffer limitations and the WBGT index was no exception [65]. So, to denote the severity of indoor heat, a new heat index needs to should be developed or the existing thresholds must be set to consider the vulnerable groups, different uses, and daily variations [66].

Also, it was stated that WBGT can provide only a general guideline for the probable adverse effects of heat [36]. The other review study by Malchaire et al., (2000) entitled "Criteria for estimating acceptable exposure times in hot working environments", explained the WBGT does not account for an ideal occupational heat stress index for the individual work situations [67]. For example, in tropical areas, such as China, India, Thailand, and Dubai, the WBGT index overestimates the amount of heat strain in people exposed to the heat [55-68]. In one of the aforementioned studies in the UAE, the average intake of hydrating fluids for construction workers per 12-hour shift was adequate (5.44 liters) under conditions that the mean WBGT values were 26.8, 28.6, 27.8, and 26.1, during the hours of 8.00, 12.00, 14.00, and 16.00, respectively. Besides, the urine-specific gravity of workers showed good hydrate status (less than 1.015). Finally, they concluded that the use of WBGT was insufficient for assessing the heat stress risk in Persian Gulf conditions and the thermal work limit (TWL) was suggested as a practical measure of heat stress in industrial settings where heat was an issue [55]. In another study conducted in Iran by Dehghan et al., (2012) entitled "Combined application of wet-bulb globe temperature and heart rate under hot climatic conditions: a guide to better estimation of the heat strain", the WBGT index was underestimated, while 47% of people who lacked the heat strain were predicted in the category of people with heat strain. The reason was likely that the phenomenon of self-pacing results in physical activity intensity. Another study showed that WBGT does not supply more realistic results of heat strain in some conditions such as warm-humid weather of the Persian Gulf, Iran, and the work/rest cycle established based on the WBGT could not be appropriate for the heat stress schedule [69]. Research results for construction workers in the United Arab Emirates (UAE) suggested that the highest and lowest mean values of WBGT were at midnight (28.6°C) and 04.00 p.m.(26.1°C), respectively, in climates with dry temperatures, high humidity, and low wind velocity. Also, it was demonstrated that the workers would self-pace in the weather conditions and WBGT was not a suitable tool for assessing the thermal risk. In the study, Thermal Work Limit (TWL) was introduced as a suitable tool to assess thermal stress in industrial settings. So, TWL measures all needed environmental parameters to take the clothing into account and supplies the metabolic rate (the output) that people can sustain in a specific environment (in $W.m^{-2}$)[55]. As an improper tool for assessing the thermal stress, the WBGT was also confirmed in another study on the heat risk evaluation in the face of heat (over 45°C)(70). Yaglou, CP. and Minaed, D. (1957) stated that no single heat value would be applicable in all situations containing the different values of WBGT, GT, and WB. Therefore, in the first version of the WBGT, they determined the correlation coefficient with sweat evaporation during the 27 training exercises over the three summer months where the WBGT described 61%, the GT 59%, and the WB 17% [27]. Hence, the most important climate factor was solar radiation and WB interfering with the evaporation of sweat. Therefore, the WBGT was an unreliable index for a warm environment [36].

C) WBGT Index and Exposure Limit Values:

According to over 50 years of studying, the WBGT index has been recognized as a standardized index by various organizations world widely [21]. If we look at the exposure limits of the WBGT index, we will see that the WBGT limit values have been determined by different organizations which were slightly different case to case. Table 3 shows the different WBGT exposure limits for acclimatized workers for well-known organizations. As shown in this table, the NIOSH limits were less severe for the un-acclimatized workers and the ACGIH limits were more severe for the acclimatized workers. Regarding the moderate load work, ACGIH has presented the WBGT limit less than the other organizations. Also, the working metabolic rates of ACGIH to ISO and NIOSH to OSHA were similar. In Iran, the OELs conform to the recommended limit values by ACGIH.

Table 3. Differences of WBGT exposure limit values for acclimatized workers [71].

Workload	ACGIH °C (W)	OSHA °C (W)	ISO °C (W)	NIOSH °C (W)
Resting	-	-	33 (117)	-
Light	30 (117-233)	30*, 32.2† (233)	30 (117-234)	30 (233)
Moderate	26.7 (234-407)	27.8*, 30.6 † (234-349)	28 (234-360)	28 (234-349)
Heavy	-	26.1 *, 28.9† (350)	25*, 26† (360-468)	26 (350-465)
Very heavy	25 (407-581)	-	23*, 25† (468)	25 (467-580)

*Low velocity; †high velocity

NOTE: Un-acclimatized workers would have greater heat expenditures during the same amount of work and temperature

Regarding the limitations of the OEL standard, it should be noted that in this standard, WBGT has been adapted by default for individuals who have used a sufficient amount of water and salt. Therefore, we believed that in the current situation where workers in the industrial environments were far from these conditions, particularly water and salt consumption, using this index as an indicator of heat stress evaluation will be accompanied by an error. This was while the organizations such as NIOSH (1986), ACGIH (2004), and ISO (1989) also have suggested limitations on exposure to the heat stress based on WBGT composition and body's metabolic rate so that with an increase in the metabolic rate the environment WBGT decreases [72]. However, because at the moment the WBGT index was the most suitable tool to indicate the exposure to workers' heat stress [73], both the ISO and ACGIH standards recommended the WBGT index as a screening tool [40-59].

D) WBGT and Physiological Parameters:

A satisfactory index of heat stress should create the same physiological and subjective responses for all combinations of its constituent elements. For example, responses to a specific level of index should be the same in warm-humid conditions, as they were in hot-dry conditions. Since the WBGT was an underestimation of the stress of restricted evaporation [8-36-60]. In a study, it was found that the physiological responses, including the heart rate, rectal and skin temperatures, sweat rate, and subjective distress of exercising men in restricted evaporation were much greater than the free evaporation at WBGT 89 ◦F (31.7 ◦C) in the laboratory tests and industrial experience [74]. Therefore, two sets of WBGT limit levels were suggested, i.e. humid conditions and dry. Also, it was argued that WBGT has a limited value for predicting the physiological strain at the higher heat stress levels which may be faced in the industry [36].

Another limitation was the difference between the values of the WBGT index and physiological index. This was because the WBGT index was an empirical index that only measures the environmental factors including dry temperature, radiation temperature, humidity, and airflow velocity, and ignores the other important non-environmental factors in heat strain such as activity intensity, work clothing type, clothing thermal insulation, personal protective equipment, age, and body mass index. However, in interpreting the results of this index, a number of these factors were used as the correction coefficients [56]. This has been demonstrated in the results of studies by Mairiaux and Malchaire [75], Bate and Schneider [55] on the relationship between physiological strains and ambient heat changes in the UAE and Australia [76]. In a case study on masonry workers in Belgium (2003), findings showed that it was not always possible in hot environments to determine the safe work-rest regimens based on the heat stress criteria, because the regimens adopted by the workers were poorly associated with the physiological parameters. The duration of each heat exposure was significantly related to the worker aerobic capacity, rather than to the heart rate level reached at the end of the working period. Finally, they suggested that self-regulation of the work-rest cycles can be an effective method to protect the workers exposed to the hot conditions from an excessive physiological strain, providing that the task had no urgent character and did not involve productivity incentives, and the workers were well-trained for their job [75]. Also, in another study on male workers of a glass manufacturing plant during the summer season in 2013, it was observed that the maximum WBGT value was 30.20±1.06 ºC. Also, among the physiological parameters including heart rate, blood pressure (systolic, and diastolic), and tympanic temperature, the highest correlation coefficient found was between the measured WBGT values and core body temperature (r=0.462) [77]. On the other hand, it was found that although the correlation between the WBGT index with ear canal temperature and PSI index was moderate, the work-rest cycle of the WBGT index was not applicable for many working stations.

A study by Gharibi et al., (2020), which was evaluated the WBGT index alongside predicted heat strain (PHS) in assessing ambient heat conditions and heat load imposed on individuals, determined that the WBGT index using core temperature and predicted rectal temperature components of the PHS index are the most consistent (kappa values of 0.614 and 0.66, respectively). While the Kappa value indicates a mismatch between the amount of water lost and the WBGT index (Kappa = 0.339). It was, therefore, preferable to measure the tympanic temperature along with heat stress measurements using the WBGT, since the relationship between these two indices was stronger than the one between water loss and the tympanic temperature [78].

E) WBGT and gender:

The WBGT index was recommended to be used in industrial working environments for both male and female workers. Meanwhile, the issue that arises, of course, was that the gender difference was not considered in the estimation tables of the WBGT index. In comparison to men, women generally have differences such as a greater amount of body fat, a higher thermoregulatory set point, and lower aerobic capacity [79-80]. Also, among women, heat loss occurs via convection, while among men through evaporation. Thus, the value of the existing WBGT may not be suitable for both genders [40,79-81]. A study showed differences in the physiological response to heat stress, physiological cost of working, and heart rate between two genders. Therefore, the WBGT index must be different for the genders [72]. Keatisuwan et al., showed that the physiological responses were different between men and women with equivalent WBGT in hot environments. Table 4 summarizes these results. They exposed randomly among 8 males and females to hot-dry (Ta=40 °C , Rh = 30%) and wet-dry (Ta=31°C , Rh = 80%) environments [82].

Table 4. Physiological responses in man and women with equivalent WBGT in hot environments [82]

	Female		Male	
	Hot-dry	**Hot -wet**	**Hot-dry**	**Hot –wet**
Δs(w/m2)	28.22±9.81	22.78±8.48*	32.17±2.99	25.53±3.8*
M(w/m2)	212.42±29.11*	212±28.47*	251.22±31.8*	236.05±28.19
Emax(w/m2)	405.24±29.11	234.74±17.58***	308.99±10.2	235.17±6.28***
W(N.D)	.45±0.08**	0.43±0.08**	0.5± 0.09**	0.55±0.13**
η (%)	98.69±2.24*	94.02±9.15*	88.45±16.28*	84.37±18.18*
$Vo2_{Rest}$ †	0.23±0.03	0.23±0.03	0.32±0.04	0.3±0.03
$Vo2_{Excercise}$ †	0.98±0.12	0.97±0.12	1.23±0.17	1.15±0.16

Δs: body heat storage, M: energy production, Emax: maximum evaporative capacity, w: skin wittedness
η: efficiency of sweat evaporation at the end of exercise(*p<0.05, ** p<0.01, *** p<0.001). † ml/kg/min.

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In a systematic review and meta-analysis, Kakaei et al., investigated the studies conducted on women as participants and found that the WBGT average values were 5.16 °C less than the results obtained for men [18]. In a review study, Emily concluded that there were a few differences in responses of men and women to exercise in hot and dry environments when women and men exercise at the same %Vo2 max. Men seem not to be more able to tolerate exercising in hot and humid environments than women while working at the same relative exercise intensity. Due to their higher bsa/wt ratio, women had more tolerance than men. Notably, the radiation plus convection facilitate heat loss [83].

Regarding the ISO 7243: 1989 standard, categorization for women work was wrong considering the results of a study by the Polish standard, where women working in industries had the highest level of physical workload, i.e. 3.7 kcal/min, i.e. 258W (1600 kcal/shift), but as per the WBGT standard, they had a moderate level of workload [84]. Also, the WBGT for pregnant women working in the industry did not consider the values that should be much lower than men [55-85]. During pregnancy (often unrecognized) a female worker’s core temperature was higher than 39 °C for a long time, and as a result, the risk of malformation to the unborn fetus increases [65].

F) WBGT Index and Acclimatized Workers:

Although the WBGT index was used globally, there was, unfortunately, no fixed value for considering the difference between acclimatized and non-acclimatized workers in different working conditions such as light, moderate and heavy work [44-73-86]. A study by Golbabaie et al., showed that the amount of WBGT in acclimatized and non-acclimatized individuals was significantly different (for acclimatized workers: 32.95±0.08 and non-acclimatized workers: 33±0.08 in moderate work) [43]. This index was not accurate for the adapted workers, because we need to estimate the accurate metabolism rate, and also we fail to take into account the direct measurement of wind velocity, reduction in work rate, place and time of work shift, and removal of clothing [76]; e.g. dry conditions of melting and casting processes.

G) WBGT Index and Measurement Errors:

The other problem was that the instruments' calibration standard procedure did not inform the user of the environmental conditions of calibration [36]. Accuracy of calibration of existing devices was affected by different temperature conditions and the working conditions of individuals, too. So, studies showed a 4°C difference in comparison made between Botsball and WBGT [8-87]. Such errors were practically problematic. For example, a difference of 3.2 °C between 27.6 °C of the WBGT for persevering the moderate work by the acclimatized people and 30.8 °C for 45-minute rest per hour was considerable [79-87]. In military training or sport, such errors could inadvertently allow exercise to be continued in dangerously hot conditions, or to be unnecessarily summarized in safe conditions [36].

Another issue that makes the use of the index difficult was the extrapolation. To use the WBGT in warmer climates, the extrapolation method outside their range of calibration is required that makes them invalid [88]. On the other hand, when the air temperature was 40 or 45 °C, the weather would be hot and it was difficult to tolerate for people, but the WBGT calculations showed that the values at 30.8 and 34.1 °C, i.e. low level, and this was one of the limitations of the WBGT and the source of errors related to their measurement [89]. Also, the WBGT was the preferred environmental heat index in occupational situations, but it did not exist at all workstations (e.g. outdoor) and did not show the humidity and air movement sufficiently [36]. As already mentioned, measuring the index may be accompanied by an error for outdoor jobs.

In conclusion and based on the abovementioned outcomes, despite the limitations mentioned for the WBGT, some researchers still apply the index for assessing the heat stress conditions suggested by ISO and ACGIH [89]. The other reason for using WBGT, irrespective of its limitation, was the simplicity and comprehensiveness of the index for assessing the thermal stress conditions. Although, its limitation and errors decrease the usefulness of WBGT [36].

Finally, Malchire's analysis stated that the WBGT index was not suitable for screening purposes [90]. However, it was confirmed by the authors of this study that it can provide only a general guide to the possibility of adverse heat effects.

Consequently, according to the literature review, there were a few limitations for the WBGT index that should be reviewed and corrected by researchers and related organizations as follows:

- The gender difference was not incorporated in the estimation tables of the WBGT index.
- To measure the average WBGT during the heterogeneous conditions in standing status coefficients 2, 1, and 1 were taken into account for waist, head, and foot, respectively, but the coefficients weren't clear for the seated status.
- The numbers inside the standard WBGT tables were presented as a single value. If the calculated number was among the table numbers, finding the exact value interpolation was necessary and should be seen as a limitation for this index.
- WBGT was used as a screening indicator; so, it seems better to add items to this index to be taken as a complete index.
- This index was designed based on the physical condition of soldiers. So the question was that can one use it for all workers in different industries?
- The index was used for adaptive people who have consumed enough water and salt. Therefore, in all hot working environments, water and salt were not always available to workers, hence using them as an index for heat stress will lead to error.
- To use this index in heterogeneous environments, placement height considered for the defined globe thermometers was commensurate with the normal individuals. Hence, how much height can be used for short or tall people?

Despite the limitations, the preconditions for the use of this index should be considered when evaluating workers exposed to heat. For example, the WBGT was a suitable and acceptable index for rapid evaluation of heat stress in the warm indoor environments with natural ventilation, temperature equal and lower 30°C, not being various weather conditions such as air-dry temperature, high humidity, and low wind velocity, and also the studied individuals use a sufficient amount of water and salt.

CONCLUSIONS

The current review was discussed the defined and non-checked limitations of the WBGT index to be used in the industrial fields.

Despite its advantages, the WBGT index faces limitations that have been mentioned in no document. To estimate the thermal stress more accurately, these limitations should be taken into consideration. In this review, we pointed out the new limitations; e.g. the height of the assessment value of WBGT for the seated persons who were working was not clear. Also, the low accuracy of the index due to the use of non-standard calibration instruments and methods, lack of separation of WBGT level for male and female workers due to the different physical, and physiological characteristics between the genders, not considering the lower values for the pregnant female workers by comparing the male and female workers, an inadequate tool for evaluating heat risk in climates with dry temperatures, high humidity, and low air velocities, etc. The additional problem with the use of this index was that it was used for adapted people who had consumed enough water and salt, while in most hot working environments neither water nor salt was always readily available. Therefore, using this index will cause an error. Also, in heterogeneous environments, if the heat source was near the head or legs, a coefficient would not be applied to these regions. i.e. one of the limitations of this index.

The results of the study demonstrated that because of the limitations of the WBGT index, it was recommended that this index be used along with other indicators and physiological parameters to assess heat stress until more extensive studies were conducted in an attempt to improve and remove its limitations. As a result of changing the limitations of the index, it may become the best and most widely used index of heat stress in occupational and especially industrial settings.

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