REVIEW ARTICLE

Comparison of Indices to Estimate Heat Exposure to Human: A Review in Tropical Regions

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ABSTRACT

Workplaces in tropical countries are associated with increasing temperature and humidity, thus, the workers are susceptible to heat hazards. The inability for self-cooling properly toward exposure to head hazards can lead to severe dehydration and even death. To date, there are several indices and models to assess heat stress, such as WBGT, ISO 7933, discomfort index, HIS, PhSI, etc. However, their accuracy and suitability for tropical regions are still under investigation since they are mostly developed for subtropical regions. This review assessed the indices to estimate heat exposure in tropical regions based on the various online database. Among those indices, WBGT is the most suitable despite its inability to estimate human thermal response in tropical regions with several adjustments. Based on this review, it showed that there is a need for improvement of current indexes to be used in tropical regions since they are more suitable for the subtropical countries.

Keywords: Heat stress, Heat strain, Tropical regions, Heat stress indices, Comfort

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INTRODUCTION

Rapid urbanisation and a developing economy in low- and middle-income tropical nations where heat stress is a concern may lead people to perform heavy labour for long periods of time in hot and humid circumstances, especially those in low socioeconomic position (1). As a result, workers are subjected to extreme heat, increasing their risk of heat-related disease and occupational harm (2). Heat stress is a health-related hazard which is commonly found in workplace both at outdoor and indoor environment. In the long term, the heat stress can originate from both external and internal factors, leading to fatigue and stress in the body. Meanwhile, internal factors determining the heat stress level will impose the human which comprises temperature of core body, natural heat tolerance, acclimatization, and metabolism produced heat of the body. All these aspects depend on the workload of the workers as the external factors that may include the ambient temperature, radiant temperature, velocity of air (air movement) (3), and air humidity. Extremely hot workplace reduces workers productivity, increases the accident risks to the workers, and the risk of heat-related disorders (4). When humans undergo high heat stress index, they can experience heat stress, leading to a condition where they fail to survive due to being too warm and unable to self-cool properly. Overexposure to high heat stress index can lead to severe dehydration and even death (1). Heat hazard constitutes physical hazard, leading to the workplace health problem and one of the vital and common problems in workplace related to occupational health issues, the condition in which human experiences inappropriate thermal state which can impact the worker's health and productivities (5).

Heat stress is a condition in which humans' bodies cannot sufficiently cool themselves to sustain a stability of internal temperature. Internal mechanisms to mitigate heat stress comprise evaporative cooling, while for external efforts, such as seeking shading area, utilisation of additional cooling space or change in schedule which enables high intensity work to be done in lower temperature-area. There is an increased number of heat-caused deaths pertaining to climate change has been found (6). With temperatures that constantly increase, it is likely that the number of deaths related to heat-related increases (7).

Due to the significantly adverse effects of heat stress on human health, various endeavours have been made to control, measure, and mitigate the effects. Heat effects measurement is classified into two categories, i.e., heat strain and heat stress. Whereas the terminology stress refers to external forces, such as environment, the term 'strain' is referred to as an object or individual's responses to the cause of the stresses (1). Determining the heat stress index is important whether workers are working outside or inside buildings. When a human is exposed to heat stress, he/she will respond to it by releasing fluid through his skin via evaporation to maintain a cool temperature. The heat stress index is defined as the combination of the amount of evaporation or perspiration an average person or individual requires in relation to his/her maximum ability of perspiration or evaporation.

There are several methods to mitigate, control, and measure, quantify the workplace heat strain and heat stress in workplaces, i.e., the deployment of heat stress and heat strain index. The use of models and heat stress index and models to estimate the quantification of both heat strain and heat stress can help reduce mortality and morbidity in various applications. For instance, broad fields of applications, such as industries, sports, military, and leisure activities, have drastically reduced morbidity and mortality due to heat stress by the utilization of models and heat stress indices. The development of over 160 various climatic stress indices has existed for the past more than 70 years, some of which, more than 100 ones are dealing with heat stress indices (8).

Although several methods in quantifying heat stress and heat strain exist, WBGT or wet-bulb globe temperature is primarily one of the widespread uses in occupational health applications. Among all the direct indices or empirical indices Goldman has reviewed, only WBGT has prevalent use for managing workplace-related heat-stress. Furthermore, the method is then used for formal applications in industries in the European and ISO standard, ISO 7243 related to hot environments, and the method to estimate heat stress on working objects, based on the WBGT-index (wet bulb globe temperature) (8). This method is based on an apparent type of temperature deployed to estimate humidity effect, wind (air velocity), temperature, and the radiation of visible and infrared light, particularly sunlight exposure to humans. The method is widespread and common for athletes, industrial hygienists, and the military for appropriate exposure levels to high temperatures. Owing to its worldwide popularity in use, it becomes the world standard of ISO 7243 given that it is suitable for widespread use. The world standard is globally accepted to control heat-related hazards in the occupational environment based on WBGT-index since it provides a simple assessment and control (9). This study was undertaken to compare indices to estimate heat exposure to humans in tropical regions.

METHODOLOGY

Relevant scientific publications were searched using the following search terms: ('heat stress' or 'heat strain' or 'tropical regions' or 'heat stress indices' or 'comfort') and ('workers' or 'plantation') (10), (11). The research screened covered a period of between the years 1990 to 2022. This large period was taken to ensure all work in this field has been sufficiently taken into account (12).

The electronic databases that were searched include BioMed Central, Springer Online, PubMed, Taylor and Francis, Elsevier and BMJ. The following journals were searched individually: Building and Environment, International Journal of lndustrial Ergonomics, Building and Environment, Industrial Health, and Indoor Air. In addition, other relevant publications were found by going through the references of some articles (10).

Conference papers were excluded from this review, firstly because they lack peer-review status and are often presentations of ongoing work later published in journals. Secondly, it would have been very hard or almost impossible to find all the conference papers relevant to this review. A selection of just a few papers from various conferences would have been a possible source of bias (10).

The target of the literature search was to find all heat stress issues and problems among plantations workers concentrating on heat exposure and heat-related symptoms. It is likely that a more complete selection of recently published papers was found, because the text of older papers cannot typically be fully searched. If a digitized version of an older paper is available, it often contains only a title, keywords, and an abstract.

The review focuses on plantation workers concentrating on heat exposure and heat-related symptoms, so studies dealing with other types of industries (metal production and processing industry, chemical and petrochemical, food processing and waste treatment) emit heat stress and causes the health issues for their workers were excluded. Only studies considering plantation industry were included.

RESULTS AND DISCUSSION

Mechanisms of heat exchange in humans
Naturally, humans exchange heat into and out of the environment by means of heat transfer mechanism via convective and radiation through skin. Meanwhile, by forced convection is done through breathing and water evaporation through the airways and sweat secretion via skin. Several environmental aspects are affecting

the heat balance of humans, such as air velocity, air temperature, surrounding surfaces temperature, and ambient air moisture content. To respond such environmental factors, human adjusts his activity levels, insulation through clothing, and resistance of evaporation diffusion through clothing. Humans can perform shivering outside the thermal comfort range while chilled and sweating when hot (13).

To maintain normal body's functionality, there is an essential requirement for human core body temperature within in very narrow range of ± 1°C to 37°C as the temperature accepted by the resting body. In order to achieve such a state of equilibrium, the human body requires a constant heat exchange with the surrounding environment. The fundamental laws of thermodynamics govern the rate and amount of heat exchange between the body and environment. Generally speaking, the heat amount to be exchanged to the environment follows the function of the total production of metabolic heat, in which it can range of around 80 watts at rest and around 500 watts for industrial workers with moderate-heavy work. At the same time, it can reach 1,400 W for a 70 kg young man athlete who is well trained. Furthermore, the heat exchange is also a function of the heat humans gain from the surrounding environment. This is approximated around 17.5 W for each change of 1°C at surrounding temperature, more or less 36°C. The heat amount which can be changed follows the sweat evaporation function, i.e., around 18.6 W for every change of 1 mmHg at ambient vapor pressure, below 42 mmHg, with the assumption that an average temperature of skin is 36°C. The general heat balance between the surrounding environment and humans are depicted using the following equation:

$$\Delta S= (M=W_{ex}) \pm (R+C) - E$$

Where: ΔS refers to the change of body heat content; ($M–W_{ex}$) denotes the production of net metabolic heat from total metabolic heat produced, while Wex is assigned for mechanical work, (R+C) refers to heat exchange via radiative and convective; and E is heat loss via evaporation. In such a situation, the thermal balance ΔS is 0, then:

$$(M-W_{ex}) \pm (R+C) = E_{req}$$

Furthermore, the equation determines the evaporation required to achieve thermal balance (E_{req}). Notably, in most of the cases, the environmental evaporative capacity is lower than E_{req}. Therefore, the environmental maximum evaporative capacity (E_{max}) must be taken into account. The E_{req}/E_{max} ratio, which denotes the skin wetness required to dissipate heat from the body, is a "heat strain index" HSI), which Belding and Hatch put forward.

Table 1: Six critical determining factors of thermal comfort (11)

Parameter	Symbol	Also
Environment		
1. Dry-bulb temperature To =0.5(Ta+MRT) (To ≈2/3Ta+1/3Tg)	(Ta)	To
2. Black-globe temperature MRT=(1+0.22V0.5) (Tg–Ta) +Ta	(Tg)	MRT
3. Wind velocity	(V)	
4. Wet-bulb temperature	(Tw)	rh; VP
Behavioral		
5. Metabolic rate	(M)	met
6. Clothing Insulation Moisture permeability	(clo) (im)	

Six leading factors to heat stress

Based on Fanger's arguments, there are six fundamental interacting factors that define humans' environmental thermal and the sensation of thermal comfort. Furthermore, the fundamental parameters are classified into subcategories into behavioral and environmental factors. The four essential environmental aspects of variables comprise flaming and surrounding temperature, moisture content and the movement of air. On the other hand, the behavioral parameters consist of metabolic rate and clothing, i.e. characteristics of moisture permeability and insulation) which can have effects on how a human responds response to a feverish environment. Therefore, the terminology of the stress caused by heat is mostly related to these six fundamental factors.

According to (14), The body of a human has been naturally created to encounter the body core temperature at the range of 37°C. However, an individual who performs physical activities, such as working, walking, etc. produces metabolic heat inside his body. Therefore, to avoid hazardous increase in body core temperature, the person requires transfer of heat to the external environment. Within the human body, the heat balance is determined with four essential factors of the environment, including air humidity, radiant temperature; air temperature; and air velocity or wind speed. Meanwhile, for the perspective of human behaviors, it consists of clothing and the generation of metabolic heat inside the body due to physical activities.

Effects of heat stress on human physiology

In general, the human body responds heat stress from environment by the physiological changes, such as an increase in sweating, body core temperature, and heart rate (15). Suppose cooling via sweating and convection heat transfer, which is performed through air movement and get contacted with cooler air which is not adequate. In such a case, the generated metabolic heat needs a reduction to avoid heatstroke and heat strain. Moreover, it will create limits to which any physical activities and work are maintained without having to take a rest. On the other hand, if there are high activities in an environment with heat exposure, the person is exposed to increased risk in core body temperature, or above the limit of 38°C. It will lead to decreased capacity of physical work, decreased mental task ability. At the same time, it will increase the risk to the accidental occurrence, and at the end, heat stroke or heat exhaustion. The increase of body core temperature is deemed for the leading cause of these heat-related problems. In addition, as the body responds to the heat via sweating or dehydration and inadequacy of liquid intake is also a primary factor in heat-related illness. Clinical disease and symptomatic exhaustion, in particular kidney-related disease is also caused by severe dehydration. Furthermore, if the temperature limit 39°C is exceeded by the body core, it can lead to heatstroke or acute heat disorders, while more 40.6°C is exceeded, it can threaten life which is so-called severe hyperpyrexia (16).

The presence of occupational heat strain is there when there are one or more criteria in a workplace, i.e., according to the international standards of occupational health and safety, when the core body's temperature exceeds 38°C. At least there is a symptom from the occupational heat strain to be defined as the guidelines of the international health and safety, the concentration of >1·2 mg/dL as an indicator of acute kidney injury, vomiting as an indicator of heatstroke, spasms as an indicator of heat cramps, serum creatinine diagnosed urinary lithiasis as an indicator of acute urine and specific gravity more than 1.020 which indicates dehydration. Furthermore, heat-associated and self-reported nausea or muscle pain, dizziness, bewilderment or unconsciousness which indicate heat syncope, heat stroke or heat exhaustion. Heatstroke is indicated with hot and dry skin sense with self-reported heat strain, which indicates heat exhaustion; and concentration of cholesterol exceeding up to 6.7 mmol/l or the concentration of low-density lipoprotein 3·4 mmol/L as a symptom of heat-induced dyslipidemia (3).

It is well acknowledged the reducing effect of heat stress on workers' capacity owing to physical inability and innate physiological reasons to move forward at the desired pace. It agrees with the workers' reported perceptions about reduced productivity due to heat stress at the workplace in the study conducted by (17).

Adverse effects of heat stress on humans

It is found that elevated heat stress might decrease an individual work capability; thus, manual labour encounters difficulty since his body is not able to dissipate heat quickly. It is expected that heat stress incidence increases as the climate change occurs. Therefore, it will decrease industrial productivity due to unsuitable workplaces in tropical regions. Economic productivity decreases as a result of the lost working time. In fact, it is essential in the tropic regions since it constitutes a significant portion of the developing countries (18).

Furthermore, heat stress may decrease workers' productivity. As stated by Wyon (1993), he found a decrease of many routine tasks by 15 – 30% due to heat stress. Below or above the optimal temperature for 6°C has been proven to significantly decrease work productivity (13). Unusual hot weather can affect human societies' work productivity by decreasing their performance at work, and it can increase some other illnesses related with the heat. Notably, the higher value of the heat stress can deteriorate outdoor labourers' work productivity in which there are demanding physical tasks. Excess heat stress will increase the core of human body temperature (over 37°C). Thus, it will lead to the heatstroke (serious hyperpyrexia), cause to decrease in the performance capacity of the physical work. Increased exposure to heat is associated with occupational health-related problems, risks and exhibits adverse impacts on work productivity.

Table II: The adverse effects of heat stress on human health (18)

HI (°C)	Risk levels	Classification	Health problems
27–32	Low	Caution	Fatigue possible with prolonged exposure and/or physical activity
32–41	Moderate	Extreme Caution	Sunstroke, muscle cramps, and/or heat exhaustion possible with prolonged exposure and/or physical activity
41–54	High	Danger	Sunstroke, muscle cramps, and/or heat exhaustion likely. Heat stroke possible with prolonged exposure and/or physical activity
>=54	Very high to extreme	Extreme danger	Heat stroke or sunstroke is highly likely

A report on study results conducted in Hong Kong of 370 onsite data sets revealed that the duration of working of the construction labours had a decrease by 0.33% with an increase in WBGT by one degree. Based on the analysis on 8,076 workers from 11 different studies, it revealed that there is 30% loss of productivity in working due to the rise of WBGT to the people who work in a single shift. There is also a report from Australia that the less productivity in labourer caused by the heat stress. It becomes the result of a reduction of global productivity up to 20%. In some tropical regions, labourers working in agricultural activities involve higher physical exertion levels, which have been influenced by the adverse effect of heat stress. There is also a report in 21 regions of the world that the productivity of laborers affected by the index of heat stress indicates a decrease in their productivity owing to the global warming climate and resulted heat stress. In addition, the low-income workers in the tropical countries and the heat stress will be present as the most significant hazard for health hazard without availability of facilities; for instance, health surveillance is not there (18).

In the long term, heat stress exposure causes muscle cramp, thermal fatigue disorders, lethargy, heat stroke, deterioration of main body organs, decreased productivity, decline in mental and physical performance, increased number of accidents, and reduced level of occupational safety (19). Study findings conducted by (20) revealed that by working in such a hot environment can lead to the heat stress that will finally reduce people's working spirit. They mentioned that emotions, motivation, perception, and office workers' mood are negatively affected in hot environments. On the other hand, Anderson revealed that the continuous and prolonged repetitive actions needed to maintain work performance and pursue work targets can cause hypertension and adverse change in workers' physiology. When workers require more effort for task completion in a hot environment, they experience the loss of working motivation, it will lead to a decrease in their productivity and they seem likely to be injured (20).

Heat stress in tropical regions

Previous research has revealed that workers exposed to hot and humid work settings, particularly in low-income tropical nations, are more likely to suffer severe injuries and illnesses (16), (21). Heat-related illness or heat exhaustion (fainting or collapse) can occur when hot weather and high humidity combined with workers' physical effort and dehydration, thereby increasing occupational injury and associated expenses as well as reducing work performance and productivity. Furthermore, heat-stress-related workplace injuries are particularly significant right now since we may expect the current heat stress problem to intensify as global warming proceeds and workplaces become even more thermally stressful (16), (21). Previous findings on occupational injury are particularly concerning, given the limited resources in middle-income tropical countries and the lack of adequate policies and recommendations on preventing and managing heat stress and occupational injury (21). Another study by (14) found that increased heat exposure on workers in tropical nations due to climate change may create psychological distress in workers by reducing work productivity, losing revenue, and disrupting daily social activities (21).

Regions located in tropical climates zone are attributed to elevated temperatures and humidity. These environmental factors cause the regions to be more prone to heat stress than the temperate or polar zone regions. Cities located near the sea are especially susceptible to heat stress as sea evaporation increases the pressure of water vapor in the air, which is a crucial heat stress component (18).

Where a health hazard related to heat stress is detected, standards provide decisions to implement the measures to reduce the presence of heat stress. These standards, more specific are ISO 7243 (WBGT, wet bulb globe temperature) and ISO 7933 (sweat required, SWreq) are established for American and European people, designed mainly for use in subtropical climates. Meanwhile, the standard scope is intended for international use, but less consideration is taken into account about how valid and usable they are in about how accurate and functional they are in industrially developed countries (3). In spite the fact, they claimed that these standards still remain applicable in tropical areas, use regardless of international heat stress requirements, which were established mainly in Europe and the United States. Therefore, there is a possibility that validity, ambiguity, and usability exist when these standards are implemented in industrially developing countries (IDCs). In addition, they may exhibit cultural incompatibility, and ignore the differences in anatomical and physiological aspects, and incompatible in practices different from the industrialized norms.

In regions where seasons are sweltering, workers are exposed to hotter workplaces than that the mechanism of human physiology are able to deal with. To protect labourers from excess heat, several standards have set heat exposure indices, one of which is generally used in occupational health is the WBGT (Wet Bulb Globe Temperature). The standard assesses the working hour proportion during which workers can sustain to work as the same working hour proportion required to rest to cool down their body temperature and maintain core body temperature less than 38°C. There is a sudden decrease in work capacity when the WBGT value exceeds 26 – 30°C. This range can be used to predict the effect of increased heat exposure resulting from climate change in tropical countries (16).

Another study regarding heat stress in tropical regions (20) found that over 20% report of respondents in Thailand often experienced heat interference when they do daily activities during the warm season. For instance, traveling and working were claimed to be as heat stress sources more frequently than doing other activities. It may be due to that they are involved in traffic or outdoor activities during hot weather. Performing other activities, such as housework, were found to result in lower heat stress than daily traveling and working. It can be justified since house works are carried out indoors and home-based activities where well-ventilated and air-conditioned rooms are properly available (20).

Standard of thermal comfortability

Moreover, Fanger's model (12) established a standard at a temperature comfort of 26°C for a sedentary individual with light clothing of 0.5 clo at air humidity of 20g/kg and wind velocity of 0.25 m/s. He then added that when the moisture is reduced to 10g/kg, it will elevate the operative temperature to 28°C to maintain a comfortable workplace. Thus, 1°C is the range of temperature values considered to result in the same effect as reducing 5g/kg humidity to maintain a comfortable environment (9). The standard to calculate the wet-bulb globe temperature (WBGT index) is natural wet-bulb temperature and dry bulb temperature. By referring to the data based on this standard with the assumption of slightly high air velocity of 0.5m/s, a decrease of 1°C in environment temperature, such as from 33°C to 32°C, it will affect similarly to a reduction of humidity of approximately 2.5g/kg. Air humidity has an important factor in thermoregulation system when sweating occurs for humans when the condition is above comfortable temperatures. In addition, predicting effect of heat stress also should take into account the workers whether they have adjusted to their surrounding environment. However, no studies have been conducted to determine the amount of time needed for thermal acclimatization. For instance, in the ISO 7243, it is stated that one week is the time required for heat acclimatization. However, it is likely to continue to improve when dealing with hot environments over several months (13).

The ISO 7730 (2005) defines thermal comfort is the mind condition expressing satisfactorily to the thermal condition. Moreover, ASHRAE 55 (2013) pointed out that there are six factors of environment and non-environment related to thermal comfortability, for instance, the temperature of air, radiant temperature, wind velocity, humidity, metabolic rate, and clothing insulation. In the 1960s, Fanger proposed the first thermal comfort indication model, and then he invented the modern term PMV (predicted mean vote) several years later. PMV is determined using Fanger's equation and using the PMV equation at the same time to predict the percentage of dissatisfied (PPD) which is determined with the following equation. The model is developed for both uses of indoor and outdoor workplaces. Fanger's model has been accepted by both ISO 7730 and ASHRAE 55 to estimate a rating scale of person's thermal comfort or discomfort (22).

$$PPD = 100 – 95 \times e^{(-0.03353xPMV4\ -\ 0.2179xPMV2)}$$

Physiological equivalent temperature or PET was established in the nineteenth century. With 0.9 clothing insulation and a low metabolic rate, the thermal equilibrium between the human body and the external atmosphere was investigated. PET was developed using the Munich Energy-Balance Model for Individuals (MEMI). Another index is sufficient temperature (ET), which takes into account three factors from the environment: wet bulb (air moisture content) and dry bulb (air temperature), and wind velocity. Meanwhile, ET is assigned to an environmental norm that includes continuous, humid air as well as the sensitivity of output thermal as it occurs in the real world.

Moreover, in 2011, the International Society of Biometeorology (ISB) established an alternative model called the Universal Thermal Climate Index (UTCI) in assessing sensation to outdoor thermal (23). UTCI is generally developed to examine the thermal sensation of the outdoor environment in which ambient air temperature, air velocity, air moisture content and radiant heat, as well as cloth insulation, are taken into account. The following equation represents the model of UTCI index:

$$UTCI = 3.21 + 0.872 \times t + 0.2459 \times Mrt – 2.5078 \times v – 0.0176 \times RH$$

Where t is the temperature (°C), Mrt is the mean radiant temperature (°C), v is the wind speed (m/s), and RH is the relative humidity of the air (percent). On the fundamental basis of the new UTCI, the UTCI-Fiala is considered the advanced type of physiological model (22).

Thermal comfort results from the thermal balance between environmental parameters and the human body as psychological and physiological behavior are affected by the environment. Meanwhile, thermal comfort models utilise both environmental factors (such as humidity, temperature, wind velocity, and average radiant temperature) and human metabolic aspects (such as level of physical activities and insulation of clothing) (19).

Thermal comfort is closely associated with heat stress from the environment and heat strain as a response of the human's body to the hot causing environmental factors. Currently, there are three indices of thermal strain in use to predict the human's responses to the heat stress from the environment, i.e., environmental indices, Thermoregulatory heat transfer models, and Physiological models (24). Among environmental indices, there are screening thresholds based on the American Conference of Governmental Industrial Hygienists (ACGIH) Threshold Limit Value (TLV), OSHA Heat Index, and WBGT. Furthermore, the indices classified into the thermoregulatory heat transfer model include ACGIH TLV Detailed Analysis which incorporates clothing/PPE and metabolic rate adjustments. Finally, the last indices classified as physiological models include Physiological Strain Index (PSI) (24).

Development of heat stress indices

Heat stress indices have been developed as a prediction of an individual's physiological strain resulting from the stress of environmental conditions. Such a prediction can introduce a safe working environment and practices to protect workers from a hazardous rising temperature of core body. The heat stress index aims to provide a single number that incorporates the primary parameter effects on the human thermal environment. It will result in varied values according to the thermal strain individual experiences when exposed to a hot environment (3). Ideally, a heat stress index is a single number that incorporates all climatic, physical, and personal factors and correlates them with one or more physiological responses (15).

There are currently over 100 indices and models to evaluate heat stress with various complexity and applicability (3). In 1905, Haldane temperature was introduced as the most appropriate measure as a single value of heat stress representation. Initially, the index aimed only to estimate the combination of environmental variables effects. Later, the index also took into account the effects of metabolic rate and clothing. It is worth noting that the assessment on heat stress using a single value that combined several variables continuously developed. Despite the fact, in in the 1970s', Belding, Gagge and later Nishi asserted that it would not be possible to establish a universal valid system to rate heat stress, primarily due to various and complexity of the determining factors interaction (11).

There have been several attempts to quantify the stress caused by different factors such as job environments and environment, calculate the physiological pressure that is associated, and combine those variables into a single index—what is known as a heat stress index. Thermal stress, on the other hand, is difficult to measure and perceive as physiological and psychological pressure aspects. For more than a century, people have been attempting to create an index that accurately describes heat stress conditions. Numerous indices have been created, and they are divided into three categories: empirical indices, logical indices, or direct indices. Since they integrate physiological and environmental variables, the first two classes of indices are considered sophisticated. However, they are difficult to calculate, and as a result, they are unsuitable for everyday use because they contain so many variables, some of which necessitate extensive measurements. On the other hand, the latter category consists of simple indices based on the calculation of specific environmental variables. Furthermore, since the indices are focused on environmental variables control, the third category of indices of more user friendly. For more than four decades, two indices have been used in this group: the discomfort index (DI) and the index of wet-bulb globe temperature (WBGT). Rationale indices are derived from equations involving the heat balance equation.

Meanwhile, empirical indices are focused on subjective and objective pressure, whereas direct indices are based on direct measurements of environmental variables. Since they are based on the heat balance equation, rational indices are considered the most comprehensive indices (19). Both behavioral and environmental factors are included in these indices. However, since there is no feasible way to record all of the necessary components to solving the equation the heat balance equation, several parameters are treated as constants. Skin temperature is regarded as a constant of 35°C in such a situation, for instant, using the "heat stress index (HSI) produced by Belding and Hatch (9).

ISO7933, also recognized as the PHS model or Predicted Heat Strain, was developed for the first time in 1989, based on the requirement of sweat rate measurement. Thermal work Limit (TWL) was then proposed after ISO 7933 to evaluate its heat stress (22).

Several studies investigated heat stress by merely utilizing temperature data without incorporating environmental humidity data. Nevertheless, humidity has vital influence on the discomfort aspect due to warming and therefore, it must be taken into account to determine heat stress index, particularly in tropical regions. There are a number of methods/indices available to determine the heat stress utilising various environmental/meteorological aspects. Several indices combine humidity and temperature, such as the National Weather Service Heat Index and Humidex. In contrast, others incorporate solar radiation as an addition (e.g., Wet bulb globe temperature (WBGT) and Environmental Stress Index) (1). There is also Heat stress index Steadman's Heat Index (HI) to estimate heat stress at a workplace.

WBGT (wet bulb globe temperature)

The WBGT index consists of the combination of the three weather approaches, such as natural wet bulb temperature, globe temperature and ambient temperature. Since these data are not widely collected at weather stations, this approach necessitates the use of this specialised tool to measure the existing natural temperature (25). Back in the beginning, when assessing a hot environment for the first time, ISO 7243 was used to conduct a quick assessment. The temperature index of the wet bulb globe was used to make the measurement WBGT (22) evaluated the wet bulb globe temperature as the climatic heat stress index in 1957. Thus, the detailed procedure was later introduced by the American Conference of Governmental Industrial Hygienists (ACGIH). Then they defined the metabolic rates and work-rest schedule with permissible heat exposure limits in WBGT units. They described the allowable heat exposure limit as the value at which 95 percent of the workers' population can be consistently exposed to heat stress without experiencing such adverse effects on health. These reference values are subsequently incorporated as the ISO of 7243. The values were taken from the premise base in which fully dressed and acclimatized the workers with sufficient salt and water intake could perform successful work without exceeding the core of body temperature of 38°C. If the values of WBGT become higher than the standard's defined reference values, ISO7933 offers a more comprehensive overview (19).

To assess heat stress using the standard, here are the following methods they used: clothing, air temperature (ta), air velocity (v), radiant temperature (tr), and humidity (rh) were measured according to ISO 7726. The values were taken at the height of 1.1 m above the abdomen (ISO 7726). Ramanathan's four-point weighting coefficient was used to calculate aural temperature (10) and mean skin temperature (tsk). Every minute, the values of the measurements were reported. Furthermore, heart rates were analyzed using Polar Sports testers, sweat loss was calculated using body mass loss, and metabolic rate was estimated using the Douglas bag indirect calorimetry process, with samples taken at 0.5, 1, and 1.5 hours.

The WBGT for all sessions in the analysis was within 33.43oC, with its deviation of 0.56oC in its result. The main aural temperature rose steadily for all types of objects, hitting ISO 7933, alarming the limit(+0.8°C) in 83 minute-period. The average of aural temperature in the end reached 37.97°C. There was not any discernible difference in temperature between the male and female workers. In addition, within the first 20 minutes, the temperature of the main four-point skin steadily increased for all sorts of the objects before flattening out at around 36°C. Notably, the male sweat loss differed substantially from the female sweat loss (p0.05); while the male worker's sweat loss was 1.155kgs (sd = 0.277) while the female worker's sweat loss was 0.657 kgs (sd = 0.0.5). However, there was such a noticeable difference between the male and female workers' heart rates, with males' being higher (p 0.05), indicating that males were under more pressure than their female counterparts. When the subject withdrew, her heart rate was 168 beats per minute. (26) discovered that when collecting tea leaves, the average heart rate was 115 beats per minute. They did not say how much heart rate was taken. However, due to the unacclimatized subjects' thermal pressure, it is presumed that the heart rates in this experiment were higher than those done in (26) samples after the two-hour exposure. Both samples had a mean metabolic rate of 126.27 W/m2 (sd = 22.76) (27, 26).

As a result, the ISO 7243 recommendation was to reduce heat stress directly, or to do a more comprehensive review. Consequently, the results showed that ISO 7243 successfully assessed the environmental pressure. These findings are relevant to (28) and (29). To summarize, the ISO 7933 reference values protect all subjects. However, they are usually overprotective, forecasting warning limit (tau = 37.8°C) with its dangerous limit (tau = 38°C) which can reach before the measured values taken. As a result, it is clear that ISO 7933 is overprotective, and the staff may have worked for longer than the allowable time limit. As a result, SWreq is incorrect (3).

ISO 7933:2018

ISO 7933:2018 was developed in CNRS laboratory in Strasbourg, France, based on some efforts conducted by (30). The standard was subjected to extensive evaluation in the laboratory and industrial environments. Furthermore, ISO 7933:2018 adopted a rational approach by using the equation of heat balance. It introduces a method to calculate the required air evaporation in order to sustain the heat balance. Based on the calculation result, the sweat rate required will be able to be approximated from which it can be possible to estimate the warning and the dangerous levels for gaining allowable exposure time in an environment provided. The following equation determines heat transfer of the body (ISO 7933:2018), in which TWL is determined through five parameters of environment (globe, wet, and dry temperature; wind speed, as well as the pressure of atmosphere).

$$M - W = C_{res} + E_{res} + K + C + E + S$$

Where M refers to metabolic rate, W denotes effective mechanical power, meanwhile, Cres is assigned for heat exchanges occurring in the respiratory tract, Eres refers to evaporative heat exchange, K and C refer to conduction and convection, while R, E, and S are assigned for radiation, evaporation and body acclimated heat storage, respectively.

A study investigating the validity of ISO 7933:2018 to predict heat stress on a human was conducted by (31). Their study used the FAME Lab PHS Calculator software (PHSFL) based on the standard to predict an individual heat strain and compared the results with other standards to check the validity of prediction. Later, they optimized the method by incorporating other ISO standards and sources from published literatures. Finally, they compared the prediction results with those from field experiment involving human participants in hot workplaces. In conclusion, they found that the prediction result based on the calculator is reliable with valid values.

Based on their finding, the standard of ISO 7933:2018 is reliable to be used to predict heat strain in hot workplace where humans encounter during working. During their study, it is also worth mentioning that they incorporated several vital parameters of metabolic rate based on ISO 8996:2004, such as age, heart rate, sex, and body mass. Thus, it validated the results based on environmental parameters. Furthermore, the study also took into account cloth insulation and mechanical efficiencies, and power and water loss during workers sweating. Based on their validity analysis, the predicted values based on the calculator (ISO 7933:2018) are comparable with those obtained from field experiments. These findings revealed that the calculator can be used to predict heat stress in the hot occupational environment.

Discomfort index

Discomfort Index (DI) is used to evaluate the level of occupant comfort. The discomfort index is an approximation using a linear formula which depends on the air temperature both the dry ball temperature and the wet bulb temperature. The method is known as the temperature humidity index (THI). The thermal scale is grouped into a range called the discomfort index (DI), a simple measurement of outdoor conditions (19). After establishing ET and determining its insufficiency to investigate the discomfort of the condition, DI was developed to address it (32). DI is proposed using the following equation.

DI = 0.4(td + tw) + 15

Where heat td refers to dry-bulb temperature and tw denotes wet-bulb temperature.

There are some studies assessing thermal comfort to population using Discomfort Index, among others that conducted by (33) in Khartoum State, Sudan, Northern Africa. The region is characterized with high environment temperature, particularly during summer with average annual high temperature was 38oC while the lowest was 16 ^{o}C. In their study, they estimated feeling of discomfort experienced by the population by determining Discomfort Index (DI) as a result from environmental factors, such as air relative humidity (%) and temperature. Later, the DI is determined using the following equation:

DI = T – (0.55 – 0.0055RH) (T – 14.5)

Where:
DI refers to the discomfort index, T denotes mean monthly temperature (oC), and RH is the mean monthly relative humidity of air (%).

Furthermore, according to Thom's discomfort condition, the condition of thermal discomfort is classified as found in Table III. Based on the environmental factor measurement, they compared with the range of Discomfort Index. However, in their study, only environmental factors, i.e., air temperature and relative humidity (RH) were measured without taking into account physiological and perception aspects of the population. Thus, this result needs further confirmation.

Heat Stress Index (HSI)
Heat Stress Index, previously known as Belding and Hatch Index, was initially proposed by (34), primarily focusing on the heat balance in the body. However, for high and low workloads, the index is not applicable. Meanwhile, Humidex is the HSI simple edition, which considers the combination of effects of ambient temperature and air moisture content (35). Meanwhile, the physiological strain index (PSI) is that which can evaluate heat strain based on physiological parameters, heartbeat, and body core temperature (36). The HSI is calculated using the following equation (3):

$$HSI = \frac{\text{required evaporative heat } (E_{req})}{\text{maximum evaporative heat } (E_{max})} \times 100\%$$

Where Ereq refers to evaporative heat loss needed to sustain thermal equilibrium in the human body, and Emax is the weather maximum evaporative capacity.

Table III. Thom's discomfort condition based on Discomfort Index (32), HSI equations and coefficients (15)

Thom's discomfort index			
Condition	**Discomfort index**		
Comfortable	< 21		
Below 50% population feels discomfort	21 – 24		
More than 50% population feels discomfort	25 – 27		
Majority of population experiences discomfort	28 – 29		
Everyone feels stressful	30 – 32		
State of medical emergency	> 32		
HSI equations and coefficients			
	Coefficients (K)		
	Shorts	**Standard clothing**	**Standard Plus coat**
$R = K_R (T_t – 35)$ $C = Kc_D 0.6 (42 – P_w)$ $E_{max} = K_{E} v 0.6 (42 – P_w)$ $T_t = T_g + 1.8 v^{0.5} (T_g – T_a)$ $E_{req} = M + R + C$ $HSI = (E_{req} / E_{max}) \times 100$	12.8 (11.0)	7.7 (6.6)	6.2 (5.3)

Where T_a = air temperature (^{o}C), T_g = Vernon globe temperature (^{o}C), T_r = mean radiant temperature which can be estimated from T_g (^{o}C), v = air velocity (m/s), P_w = water vapor pressure of ambient air (mmHg), M = metabolic rate of body heat production (W (kcal/h)), R = radiant heat exchange (W (kcal/h)), C = convective heat exchange (W (kcal/h)), E_{req} = an expression of stress in term of requirement for evaporation of sweat (W (kcal/h)), and E_{max} = maximum evaporative heat loss which can be achieved at a given P_w and v (W(kcal/h)).

The HSI index is based on typical human characteristics, such as 1.7 m height, 70 kg weight, and 1.8m^2 body surface area, clothing consisting of shorts and exercise shoes, a skin temperature of 35°C, and uniform sweating over the entire body. The standard coefficients can be modified by multiplying by A/1.8 if the person's surface area (A) differs significantly from that of the average human. The coefficients for shorts and standard clothing have been experimentally validated, and the coefficients for standard clothing plus coat can be calculated by extrapolating these values. In this index, the authors also determined that the maximum capacity of an average human in sweat production through an eight-hour period is 1 liter per hour. This value is equivalent to an evaporative heat loss of around 698 W (600 kcal/h). Thus, the value of maximum evaporative heat cannot exceed the value of 698 W.

HSI value can be determined using equations contained in table below. In addition, this index can also be determined using nomograph (15).

Universal Thermal Climate Index (UTCI)
Universal Thermal Climate Index or UTCI for short is used as a measurement of heat stress in an outdoor environment. The index was developed in 2009 by the representative of leading human thermo-physiological experts, physiological modelling, meteorology, and climatology through international cooperation (37). According to the authors, there are several general ideas of UTCI among others, was to attain thermo-physiological significance across all ranges of heat exchange. It also aimed to be applicable for the human body calculation, local skin cooling. The index was also intended to reliable for all climates and seasons, as well as temporal, spatial whether in micro and macro-

climate. Moreover, the index is expected to be useful for application in the field of impact of climate to humans, public health services, etc., and it also represents an index for temperature scale.

UTCI (VER, A002) calculates UTCI based on air temperature, average radiant temperature, wind speed, and air moisture content. New indices of heat stress, one of which is the UTCI (Universal Thermal Climate Index), are developed based on the human body's heat balance mechanism. The ideal heat-stress method's assessment requires considering every aspect of heat generation inside the human body and all heat exchange routes between the body and the outside environment. Thus, the ideal model fully assesses the human heat balance using the following equation:

Heat storage in the body = heat production – heat loss

S = M – (W + C + R + K + E + Resp)

Where S refers to heat storage in the body, M denotes heat production, W refers to work rate. Meanwhile, heat loss is represented by some of the heat exchange components, such as conduction (K), convection (C), evaporation (E), radiation (R), and respiration (Resp).

Moreover, after extensive evaluation, the advanced multimode Fiala model of thermoregulation was established. In the Fiala model, human is classified into two systems of thermoregulation, as active and passive thermal control system. Moreover, the model also attempts to predict human's responses in form of dynamic perception as a result of physiological state. In passive system, human is assumed as a multi-layered and multi-segmental of human body, together with its physiological and anatomical properties. The model is represented by a person in average whose mass of 73.5 kg, content of fat of 14%, and Dubois area of 1.86 m2. Furthermore, according to this model, human is assumed to have cylindrical and spherical shaped elements, composed of layers of tissue, characterized to have thermophysical and physiological functions. Meanwhile, in the perspective of active control system of UTCI-Fiala model, the human body responds thermal environment with specific reactions based central nervous system, such as elevation (vasodilatation) of cutaneous blood flow, shivering thermogenesis, suppression (vaso constriction), and sweating or moisture excretion (37).

Tropical Summer Index (TSI)
The tropical summer index, which was initially proposed by Sharma and Sharafat (21), refers to the given environment in which the temperature of calm, still air, at relative humidity of 50% which conveys the same thermal sensation under investigation. In their study, 18 fully acclimatized young males were studied for three consecutive summers in India from May to July. Using multiple regression analysis, the equation describes thermal sensation experienced by the objects of the study in response to thermal exposure. Based on the equation, Tropical Summer Index was later developed which is comparable with several existing heat indices.

In Tropical Summer Index, four environmental parameters are taken into account, i.e., air temperature, globe temperature, air humidity, and air velocity, which proportionally affect human's thermal sensation (21). This index was established based on the environmental variables' multiple regression analysis on thermal sensation (22). The TSI is solved using an equation similar to that of WBGT as follows:

TSI = 0.30 Tw + 0.74 Tg – 2/06 (V + 0.841) 0.5

Where Tnw refers to natural wet temperature, Tg is radiant temperature, and V refers to wind velocity.

It is seen that the values of TSI almost agree for all practical purposes, over the wide range (24-40 °C). Range of temperature which is determined in Tropical Summer Index, such as TSI more than 34°C defined as 'too hot', TSI from 30 – 34°C is considered tolerable warm, TSI from 25 – 30°C is defined as thermal comfort, while TSI from 19 – 25°C is considered tolerable cold, TSI less than 19°C is regarded as too cold. The range between tolerable warm and tolerable cold is defined as extensions of the comfort band, in which thermal comfort can be regulated by metabolic activity or clothing adjustment (3).

Comparison among heat stress indices
Heat stress is closely correlated with human's responses in terms of heat strain. Although the study investigating this aspect has been well established, there is no universal index that can measure heat stress and heat strain for varied types of area. The comparative study which carefully investigated different measurements on heat stress is conducted, among others by (13). Heat strain, as responses of human physiology to heat stress from the environment is closely interrelated to each other. For instance, (16) stated that heart rate would increase as body heat accumulates. Furthermore, sweating rate can also increase with body core temperature elevates.

So far, there are more than 100 indices have been developed to facilitate the assessment of thermal environment. However, (37) argued that most of the indices have minimal applicability since they cannot figure out the actual impact of the thermal environment on human body. Furthermore, instead of merely relying on bioclimatic factors, they suggested that indices derived from the heat balance model in the human body, either it is one- or two-node provide more reliability to depict the representation of thermal environment impacts.
The wet-bulb globe temperature or WBGT index for short is the most popularly used among all the heat

stress indices. This index incorporates a number of critical variables of the environment to assess heat stress. It has verified performance with microclimate variables measurements. Nevertheless, this index cannot estimate the thermal response of human. Therefore, Moran et al. suggested a physiological strain index (PhSI) which is considered more accurate to predict the human's physiological strain overall state. However, the PhSI index is predominantly regulated by increased heart rate, and slow responses to changes in core temperature. As some researchers achieved a better knowledge of heat exchange between human body and the ambient environment, they are able to formulate more sophisticated and accurate rational indices. It is (38) who first proposed the predicted heat strain (PHS) model according to the human body thermal equilibrium. The estimated values of rectal temperature skin temperature (Tsk) and sweat rates (SR) are gathered via non- intermittent iteration of the relationship between skin moisture content, evaporative cooling capacity, the efficiency of sweat evaporation, and ability of maximum perspiration. Such indicators can more accurately predict than the model of required sweat rate (SWreq) in ISO 7933. Thus, in 2004, the ISO 7933 standard adopted this model to predict heat stress (37).

Meanwhile, WBGT index only takes into account several environmental parameters, such as wet bulb and dry bulb temperature, solar radiation, air velocity, while put aside physiological data, covering skin temperature, heart rate, blood pressure, and abdominal temperature as body responses (heat strain) to the environmental factors known as heat stress. In fact, heat stress as thermal load on the body results from the combination of several factors, such as heat from the environment, air humidity, air velocity, metabolic workload, and type of clothing (39). Therefore, in practical applications, WBGT is often incorporated with other physiological and perception data. Furthermore, slightly modified, in ISO 7243, WBGT factors are taken from several point measurements, which include head, abdomen, and feet (13). Furthermore, several measurements incorporate other parameter to overcome the limitation of this index, such as ACGIH (American Conference of Governmental Industrial Hygiene).

On the other hand, unlike WBGT and Discomfort Index (DI), Heat Stress Index (HSI) incorporates both human aspects, i.e., physiological factors, including thermal energy excreted from human body caused by evaporation for achieving thermal equilibrium. This heat stress index is able to take human's body responses to heat stress from surrounding into consideration in its measurement. It can be seen from the determination of body metabolism, together with solar radiation and energy exchange by convection manner. However, this index does not take air velocity and air moisture content into a measurement to determine heat stress. In fact, such factors are vital in determining thermal comfort among workers in hot workplace. It is well acknowledged; the same intensity of solar radiation impacts differently to humans in humid and arid regions (Table IV).

There has never been a well-defined approach or process for selecting an acceptable heat stress index for tropical climates, although there are numerous heat stress indices. As a result, environmental engineers have had to rely on intuition and guesswork to choose a heat stress index or indices. Our research provides a useful tool for evaluating and selecting the best appropriate index for tropical climatic conditions in order to safeguard outdoor workers from heat-related illnesses. Despite its complexity, the method produces results that are easier to perceive and comprehend than any

Table IV: Comparison among heat indices for tropical regions

Heat stress index	Advantages	Limitations	Reference
Wet Bulb Globe Temperature (WBGT)	Most applicable index to measure heat stress. Incorporates four environmental parameters, temperature, humidity, air velocity and radiation, Incorporate type of clothing, type of skin, simple prediction of heat stress, high applicability for industries, good correlation with physiological responses, measuring instrument has small and simple size	Physiological factors not taken into account, poor estimation under low humidity environment, inconsistency of physiological meaning at the same WBGT value, higher inconsistency in higher air temperature, metabolic workload not taken into account,	(13), (15)
Tropical Summer Index (TSI)	Well applicable to the prevailing hot-dry and warm-humid environment	Only environmental variables taken into account, metabolic workload not accounted,	(21)
Universal Thermal Climate Index (UTCI)	Incorporates physiological and environmental aspect, heat exchange between human- environment, predict human perceptual and physiological responses to thermal exposure, considered one of the most comprehensive for heat stress measurement in outdoor environment	Quite complicated in use, UTCI more appropriate for assessing heat stress in low humidity and temperature environment	(37), (40), (41)
Heat Stress Index (HIS)	Incorporating both human physiological aspects and environmental factors, able to estimate tolerance time and required resting time, has been widely used to evaluate hot workplace.	Difficult implementation to variable or intermittent heat exposure, only valid for young acclimatized, requires complicated calculation, underestimates hot humid and low wind velocity	(15)
ISO 7933:2018	Extensively evaluated in laboratory and industrial environment, both environmental parameters and physiological aspects are accounted,	Assumption that subject workers are hydrated and fit. The subjects are small size of European population which does not encounter with extreme environmental workplace	(31), (25)
Discomfort index (DI)	Heat strain put in simplicity, has been used for more than 4 decades, good correlation with thermal sensation, such as sweat rate	Only environmental factors, wet and dry temperature taken into consideration, solar radiation not accounted	(33), (21)

other evaluation approach now available. It also has the added benefit of allowing simple indices to be evaluated using physiological comfort indicators. More studies are needed, however, to improve the process and test the climatic model so that it can reliably analyse tropical climatic conditions and determine the most appropriate and safe index to safeguard outdoor workers.

CONCLUSION

variables are deemed to have little industrial applicability due to the inability to assess and portray the actual impact of thermal stress on human body. Instead, to establish more reliable and validated heat stress indices, heat transfer and heat exchange, heat balance between human and his environment should be taken into consideration for better representation of heat stress impact on human body.

As well acknowledged, the existing heat stress indices are primarily suitable for use in the northern hemisphere of temperate regions with cool climates. As tropical regions characterised to have higher temperature and humid climate, using the indices requires scrutinies according to empirical data. The use of WBGT method in predicting heat stress and estimate strain in the human body for tropical regions should incorporate other physiological and perceptual data, similar to the method proposed by the American Conference of Governmental Industrial Hygienists (ACGIH) for tropical regional purposes. This index can derive the environmental parameters, i.e., air velocity, dry and wet bulb temperature, and solar radiation using a quick and straightforward measurement. Later, to estimate the heat strain workers are most likely to encounter, further studies need to be conducted to establish a universal relationship between the environmental measurement, human physiological changes, and perceptual consequences.

For workers in tropical developing nations like Malaysia, urbanisation will exacerbate these problems. In such situations, injury interventions must include initiatives to reduce occupational heat stress. There is a need for further research for a bespoke index to estimate heat exposure to human in tropical regions, and the current indexes are more inclined towards the developed countries in the nothern hemisphere. Thus there are room for improvement for the tropical regions.

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