The Evaluation of Comfort Indices for a Subtropical Protected Culture[1]

Chiachung Chen [2], Jiunyuan Chen [3] and Ling-Hsi Chen [4]

ABSTRACT

The types of protected culture in subtropical regions included rain shelters, shading nets, and high tunnels. High temperature, humidity, and solar radiation affect workers in these internal environments, so it is necessary to determine the method to alleviate heat stress. Several comfort indices were compared using the measurement data: the wet bulb globe temperature index (WBGT), the predicted mean vote (PMV), and the ultraviolet index (UVI). The microclimate data for air temperature, air humidity, air velocity, solar radiation intensity, ultraviolet radiation intensity, and workers' body temperature is collected in a rain shelter in Summer. These indices were calculated with the measurement data. These results show that all the UVIs were higher than the threshold of 3. The WBGT and PMV are the most relevant indices for human conditions in a microclimate with a protected culture. The improvement method is analyzed using these indices and these affecting factors. Reducing solar radiation intensity using an anti-ultraviolet umbrella and enhancing ventilation with a portable fan alleviates stress for workers.

Keywords: comfort index, predicted mean vote, wet bulb globe temperature index, protected culture

Introduction

The area of protected culture has increased yearly. These structures are simple and inexpensive. Most protected structures are rain shelters, shading nets, or high tunnels. These structures allow crops to be cultivated for an extended period. However, the microclimate in these

---

[1] Contribution No.1047 from Taichung DARES, COA.
[2] Professor, Department of Bio-industrial Mechatronics Engineering, National Chung Hsing University
[3] Researcher, Africa Industrial Research Center, National Chung Hsing University
[4] Associate Researcher of Taichung DARES, COA.

structures cannot be controlled because their control systems are limited. Commonly used devices include top vents and side vents that are adjustable manually.

The environmental issues for these protected cultures for laborers include high radiation, high temperature, low humidity, and lack of ventilation. The relative humidity is extremely high in greenhouses with poor ventilation and dense crops. Crops adapt to environmental stress, but information about workers' endurance in the protected culture is rare.

The international thermal comfort standards are established using a theoretical analysis of human heat exchange and the measurement data for climatic chambers(1).

Hopper (5) proposed a Physiological Equivalent Temperature (PET) index that used the Energy-balance model for an individual and showed that the PET value for a sunny day is greater than that for wintertime or a windy day.

Nikolopoulon *et al.* (10) defined the Actual Sensation Votes (ASV) index. The affecting factors include air temperature, relative humidity, wind speed, and the difference between a black globe temperature and the air temperature. A physiological model is used to characterize the thermal comfort conditions for humans outdoor. The ASV index is a dependent variable, and the microclimate factors are independent variables. However, the coefficient of determination for this empirical equation is 0.1521. Huang (6) studied the air temperature thermal comfort index for individuals in outdoor environments to determine the effect of clothing and showed that psychological aspects have a major role in the outdoor comfort index.

Turco *et al.* (14) studied the estimated black globe temperature using meteorological data and two empirical equations for day and night. They showed that bioclimatic indices could be determined using this black globe temperature and other environmental measurement data. Matzarakis and Amelung (7) evaluated PET as an indicator of the impact of climate change on thermal comfort for humans. Eight ranges of PET values were proposed to grade thermal perception by human beings. Tseliou *et al.* (13) evaluated three biometeorological indices for human thermal comfort: the Temperature Humidity Index (THI), the wind chill index (k), and the PET value. These results show that three indices strongly correlate with the mean climatic temperature. The study showed that a new index is required to transform each existing index.

Pantavou *et al.* (11) used four biometeorological indices to evaluate human thermal comfort: Thermal Sensation - Ginovi method (TS), the Discomfort Index (DI), the Heat Load Index (HL), and the ASV values. The measurements were air temperature, surrounding ground surface temperature, relative humidity, air pressure, wind speed, and solar radiation. The estimated ASV values are classified into different ranges of thermal comfort. This index corresponds with the TS, DI, and HI values.

Nagano and Horikoshi [9] proposed a thermal comfort index for outdoor, non-uniform environments. The factors are air temperature, relative humidity, wind speed, and longwave radiation. Orosa and Oliveira [12] proposed a method to determine thermal comfort that compares adaptive and PMV models. However, this study does not involve outdoor conditions. Chen and Ng [2] reviewed the outdoor thermal comfort index for urban planning. Prediction tools are required to incorporate the measuring instrument and assessment models. This method is used for urban planning in terms of the use of outdoor space. Coccolo *et al.* [3] proposed an 11-point thermal sensation scale to determine outdoor human comfort and thermal stress. The study showed that indices depended on the special needs of researchers.

To the author's best knowledge, no comfort indices have been proposed for workers in protected cultures. This study evaluates three indices to ensure the thermal comfort of workers.

1. The comfort indices

Three indices are used for this study: the PMV index, the WBGT index, and the UVI. These indices pertain to an outside environment with high temperatures, high relative humidity, and high solar radiation levels.

(1) PMV index

This index was proposed by Dr. Fanger [4] and is adopted by ASHARE [1].

Human metabolic rate (M_n) = convective heat from the skin (Q_c) + radiation heat loss from the skin (Q_R) + evaporative heat loss from the skin (Q_e) + convective heat loss from respiration (Q_{res}) + evaporative heat loss from respiration ($Q_{e,res}$) (1)

The human metabolic rate is affected by workloads. Tillage and harvesting in a protected culture involve workloads between 230 and 260 W/m^2 。

A. Q_c: convective heat from the skin

$$Q_c = K_s(T_{skin} - T_a) \quad (2)$$

where

T_{skin}: Skin temperature, ℃

T_a: Air temperature, ℃

K_s: Surface convective coefficient, W/m^2·K

$$K_s = C_1 K_{st} \quad (3)$$

where

K_{st}: Surface convective transfer coefficient for clothes in W/m^2·K

C_1: Modified constant

$$C_1 = f(V, W_s) = exp(a_0 + a_1 V + a_2 V^2 + b_1 W_s + b_2 W_s^2) \quad (4)$$

where V is the air speed in m/s and W_s is the walking speed of the laborer in m/s. In a protected culture, V is close to zero, and W_s is very slow; the C_1 is assumed to be 1.0.

B. Q_R: radiation heat loss from the skin

$$Q_R = h_r F_{corr}\left(T_{skin,K} - T_{mrt}\right) \tag{5}$$

where

h_r : Radiation transfer coefficient, $W/m^2 \cdot K$

F_{corr}: Corrected coefficient

$T_{skin,K}$: Human skin temperature, K

T_{mrt}: Mean temperature of the surroundings, K

$$h_r = \sigma C_2 \left[\frac{T_{skin,K}^4 - T_{mrt,K}^4}{T_{skin} - T_{mrt}}\right] \tag{6}$$

σC_2: Constant

$$T_{mrt} = (\alpha k \cdot C_3 \cdot \mathrm{I}) \cdot 0.25 \tag{7}$$

αk: Absorbance of the skin

C_3: Constant

I: level of solar radiation, in W/m^2

C. Q_e: evaporative heat loss from the skin

$$Q_e = K_{ev} C_4 (P_{sk} - P_a) \tag{8}$$

where K_{ev} is the evaporative transfer coefficient in $W/m^2 \cdot K$ and C_4 is a constant.

$$K_{ev} = K_{sev} C_1 \tag{9}$$

where K_{sev} is the basic evaporative coefficient of the human body in the rest state; C_1 is calculated using the equation, same as equations (3) and (4). P_{sk} is the surface evaporative pressure in kPa, and Pa is the air pressure in kPa. For high temperature and humidity, P_{sk} is similar to Pa.

D. Q_{res}: convective heat loss from respiration

$$Q_{res} = m_{res} C_p (29 - 0.8T_a)/A \tag{10}$$

where m_{res} is the human respiration rate in kg/s, C_p is the specific heat of the air in kJ/kg·K, T_a is the air dry bulb temperature in ℃, and A is the surface area of a human body in m^2. If $T_a > 36.3°C$, the Q_{res} becomes negative, so if the air temperature in a protected structure is higher than 36.3℃, Q_{res} does not release heat from individuals in the structure.

E. $Q_{e,res}$: evaporative heat loss from respiration

$$Q_{e,res} = m_{res} L_{at} (W_{ex} - W_a)/A \tag{11}$$

where L_{at} is the latent heat of the water in kJ/kg, W_{ex} is the absolute humidity of respiration vapor in kg·H_2O/kg·dry air, and W_a is the absolute humidity of the ambient air in kg·H_2O/kg·dry air. In high temperature and humidity situations, $W_{ex} \approx W_a$.

The above values of the constants and coefficients in these equations are adopted from Fanger [4] and ASHARE [1].

The heat load on humans is defined as:

$$L = \frac{1}{A}\left(M_n - Q_c - Q_e - Q_R - Q_{res} - Q_{e,res}\right) \quad (12)$$

If L is positive, the load is a hot load. If L is negative, the load is a cool load. The PMV index is calculated as follows:

$$\text{PMV} = [0.305 exp(-0.036 M_n/A) + 0.0275] \cdot L \quad (13)$$

(2) WBGT value

For a solar environment, the WBGT equation is:

$$\text{WBGT} = 0.7T_w + 0.2T_g + 0.1T_a \quad (14)$$

where T_w is the wet bulb temperature, and T_g is the black globe temperature.

The standards for durations of work for workers in high-temperature conditions are listed in Table 1 [8].

(3) Ultraviolet Index

The UVI is measured as a standard to express the intensity of the ultraviolet radiation from the sun at a particular place on a specific day. The method for calculating the UVI recommended by World Meteorological Organization (WMO) and World Health Organization (WHO)[16]. The exposure categories of UVI are shown in table 2.

Materials and methods

1. Protected structure

A 21.6m×40m×4.5m, plastic-glazed steel-framed structure rain shelter in Silou, Yunlin county, Taiwan, is used for this study. This area is the major production site for vegetables in Taiwan. This area has a subtropical climate. The transmittance is 80% for covering materials. Vegetables are grown on the ground.

2. Measurement devices

The air temperature and relative humidity of a greenhouse and inside air were measured using a Shinyei THT-B7 resistive-type transmitter (Shinyei Kaisha Co., Kobe). The accuracy of these sensors is less than 0.7 % after calibration using a saturated salt solution. The air temperature and relative humidity sensors were placed in a radiation-proof box with a fan.

The interior solar radiation was measured using an E8-48 pyranometer (Eppley Co., USA). The air velocity was measured using a TSI 8450 air velocity transducer (TSI Co., St. Paul, MN USA). The measuring range for air velocity is 0 to 20 m/s and the accuracy is ±1.5%. The black globe temperature was measured using a TR-31B black global sensor (Rixen Tel. Co., Taipei, Taiwan). The measuring range is -20 to 80 ℃ and the accuracy is ±0.3℃. The temperature of human beings was measured with a BRAUN IRT-3020 thermoscan (Braun Co., Melsungen, Germany). The measuring range is 34 and 42.2 ℃, and the accuracy is ±0.1℃. All of the signals from these devices, except the ultraviolet radiation, were collected by a Delta-T2e data logger (Delta-T co, UK). The interval (t_{ri}) was set as 30 s. Ultraviolet radiation was measured with the TR-74Ui illuminance & UV Logger. The measuring range is 0.1 to 30 mW/cm^2 from 260 to 400 nm. The spectral response and the accuracy are ±5%. Human body temperature was measured with the Lutron TM909A infrared thermometer. The measuring range is -20 to 150 ℃, and the accuracy is ±1.2 ℃. The interval was set as 5 minutes. The microclimate data for the protected structure for this study were measured from April 11 to May 4, 2013.

Results and discussion

1. Microclimate of the protected structure

The temperature and WBGT values calculated with equation (14) and measurement data for typical days are shown in Figures 1-3. All related indices are calculated and discussed in the following paragraph. Other measurement datasets have similar results.

2. PMV index

Data distribution of microclimate in the rain shelter is shown in figures 1 and 2. The PMV value of 2 stands for a warm and comfortable environment; the PMV value of 3 stands for an environment with heat stress. Most of the calculated PMV values in Figure 2 ranged from 2 to 5. Cases of heat stress with a value for PMV > 3.0 occur from 7:30 am to 5:30 pm on sunny days, so workers experience significant heat stress during this period. In these figures, the comfortable regions were limited.

3. WBGT index

The WBGT index is shown in Figure 3 for different periods and is greater than 32 ℃ during the day. The environment of the interior of a protected structure for vegetables in subtropical regions features high temperature and high relative humidity. Typical temperatures are T_a=35℃ and T_w= 33℃. The difference between the WBGT and the air temperature is 10-15℃ inside a structure without shading and 3-8℃ where there is shading space. These WBGT values are significantly higher than the safety standard.

4. UV index

The UV index from 11:00 am to 4:00 pm ranges from 3 to 5 is shown in Figure 4. The safety level for the UV index is 3. Common damages due to UV include sunburns, eye damage such as cataracts, skin aging, and immunosuppression.

5. Discussion

The greenhouse microclimate in the temperate region was maintained at 20-25℃, and relative humidity was maintained at 40-70%. Solar radiation was limited to allow operators to work comfortably in the environment. However, the environmental conditions in protected structures in subtropical regions feature high temperatures, high humidity, and intense solar radiation. The comfort indices all indicate that workers are under physiological stress.

These indexes and affecting factors show that environmental stress for workers in a protected structure can be decreased using the following methods:

1. Environmental control of microclimate so the temperature and humidity are appropriate adjustments.
2. Inhibit entry of solar radiation into the structure, especially UV radiation
3. Increase the air velocity over the surface of human bodies.

There is no suitable environmental control equipment so the microclimate in a protected structure is not easy to control. A practical method to reduce stress for workers is to reduce the UV energy and increase the airflow speed over the body surface. A portable fan and a UV-resistant umbrella can reduce heat stress.

This study uses three indices to evaluate heat stress for workers in a rain shelter in subtropical weather: the wet bulb globe temperature index, the predicted mean vote, and the ultraviolet index. The microclimate data includes the air temperature, the body temperature of workers, the air humidity, the air velocity, the solar intensity, and the ultra-light energy in summer. The results show that the PMV, WBGT, and UVI indices accurately express human conditions in the microclimate of protected culture. These indices and affecting factors are used to propose a method to improve conditions in the protected structure. By these indices, the intensity of solar radiation can be reduced using an umbrella, and evaporation from the human body can be enhanced by increasing ventilation using a portable fan.

Table 1. Standards for working time in high-temperature conditions of the Ministry of Labor

The ratio of working		Continuous working	25% rest 75% working	50% rest 50% working	75% rest 25% working
Hour average WBGT（℃）	Light	30.6	31.4	32.2	33.0
Hour average WBGT（℃）	medium	28.0	29.4	31.1	32.6
Hour average WBGT（℃）	Heavy	25.9	27.9	30.0	32.1

(Source: Ministry of Labor. Occupational Safety and Health Administration, Regulations for the Standard of Work and Rest Time for High-Temperature Work[8])

Table 2. The exposure category and UVI [15]

Exposure category	UVI
Low	1-2
Moderate	3-5
High	6-7
Very high	8-10
Extreme	>11

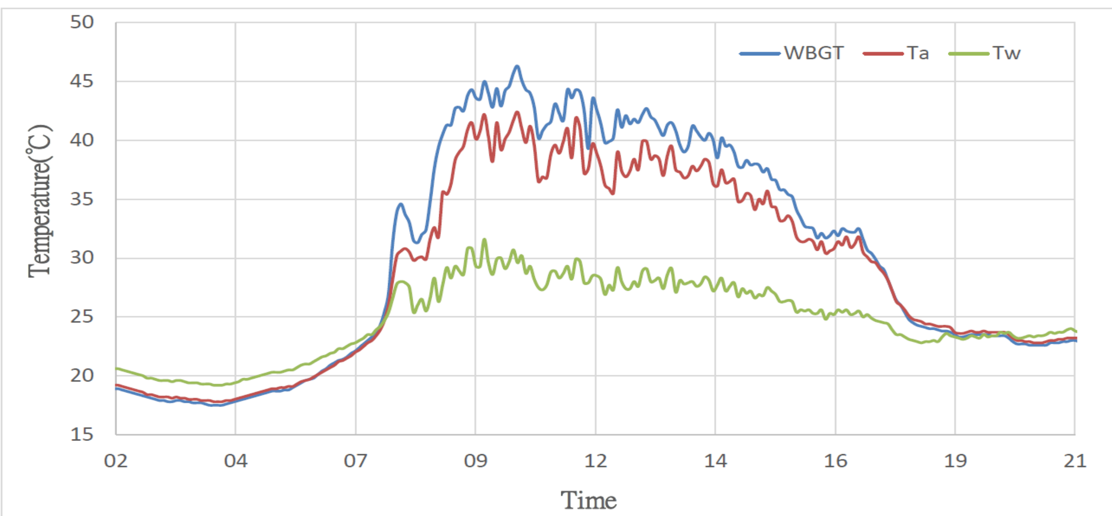
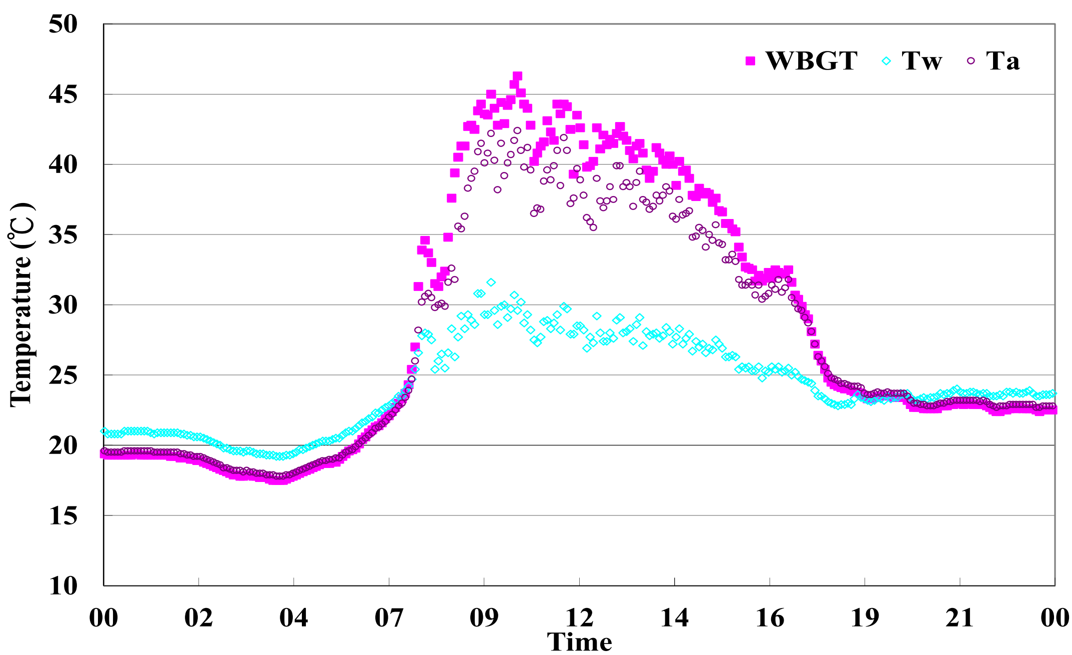
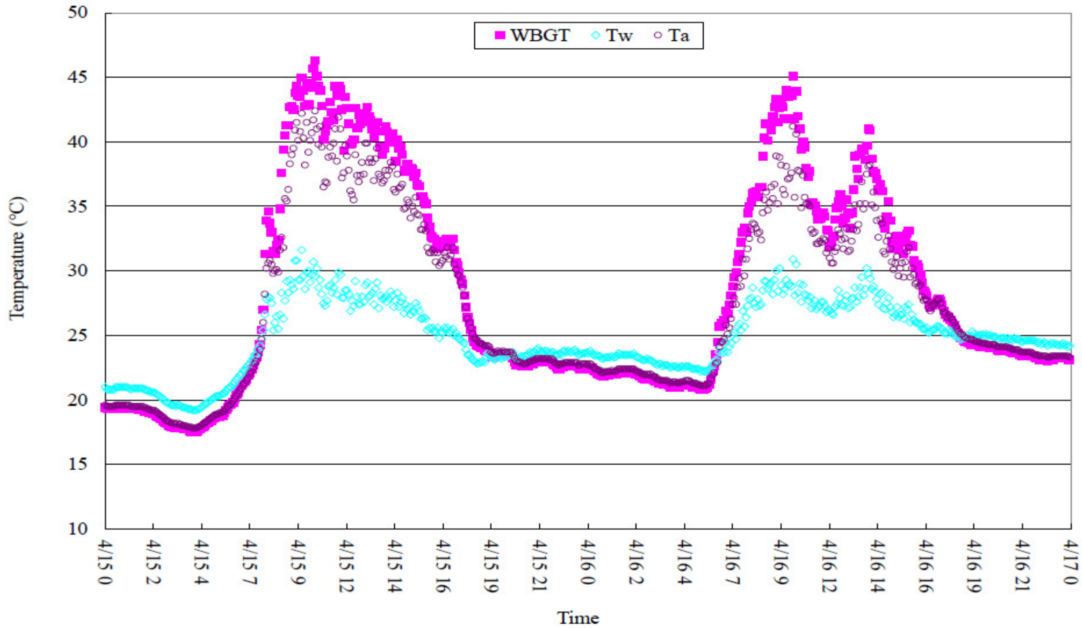


Fig. 1. Data distribution of three temperatures in summer day.

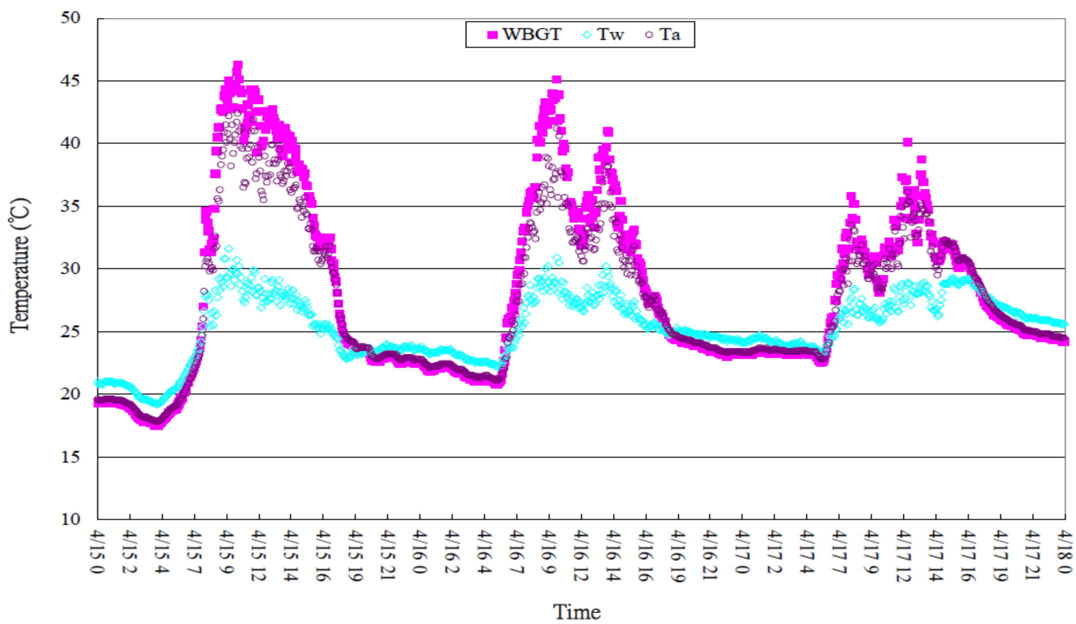
Fig. 2. The calculated PMV values.



(A)April 15



(b) April 15-16



(c) April 15-17

Fig. 3. The temperature distribution and calculated WBGT values.

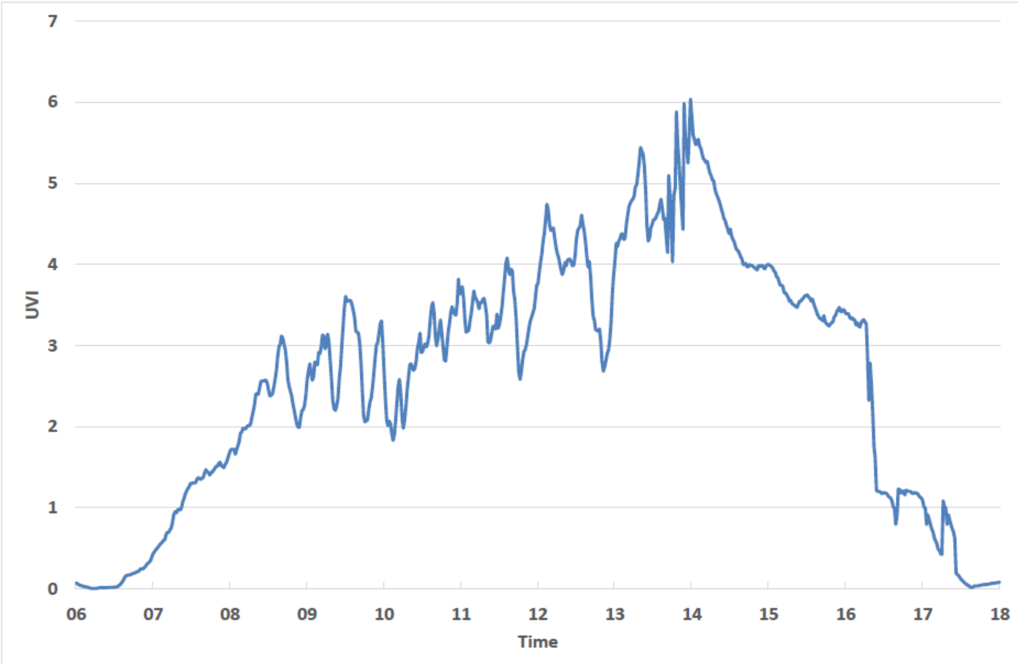


Fig. 4. The UV index values during the daytime, which have high indices of 3 to 5 from 11:00 am to 4:00 pm.

Conclusion

Several comfort indices were compared: the wet bulb globe temperature index, the predicted mean vote, and the ultraviolet index. These indices were calculated with the measurement data. These results show that all the UVIs were higher than the threshold of 3, that workers are under physiological stress. The WBGT and PMV are the most relevant indices for human conditions in a microclimate with a protected culture.

The improvement method is analyzed using these indices and these affecting factors. Reducing solar radiation intensity using an anti-ultraviolet umbrella and enhancing ventilation with a portable fan alleviates stress for workers.

References

1. ASHRAE Standard 55. 2004. Thermal environmental conditions for human occupancy, ASHRAE Inc., Atlanta.
2. Chen, L., and Ng, E. 2012. “Outdoor thermal comfort and outdoor activities: A review of research in the past decade.” Cities 29:118-125.

3. Coccolo, S., Kämpf, J., Scartezzini, J. and Pearlmutter, D. 2016. Outdoor human comfort and thermal stress: A comprehensive review on models and standards. Urban Climate18:33-57.
4. Fanger, P. 1970. Thermal Comfort: Analysis and applications in environmental engineering. McGraw-Hill, New York.
5. Hoppe, P. 1999. “The physiological equivalent temperature - a universal index for the biometeorological assessment of the thermal environment.” Int. J. Biometeorol.43:71-75.
6. Huang, J. 2007. “Prediction of air temperature for thermal comfort of people in outside environments.” Int. J. Biometeorol. 51:375-382.
7. Matzarakis, A. and Amelung, B. 2008. Physiological equivalent temperature as indicator for impacts of climate change on thermal comfort of humans. In: Seasonal Forecasts, Climate Change and Human Health, M.C. Thomson *et al*. (eds.) Springer.
8. Ministry of Labor. 2022. Occupational Safety and Health Administration, Regulations on the Standard of Work and Rest Time for High Temperature Work. https://oemd.osha.gov.tw/exposure/content/about/About1.aspx?enc-=82FD65A08BAB4CF7120EF8A1F036AB39 access: Jan. 03, 2022.
9. Nagano, K. and Horikoshi, T. 2011. “New index indicating the universal and separate effects on human comfort under outdoor and non-uniform thermal conditions.” Energy Build. 43:1694-1701.
10. Nikolopoulou, M., Lykoudis, S. and Kikira, M. 2003. Thermal Comfort in Outdoor Spaces: field studies in Greece. In: 5th International Conference on Urban Climate, IAUC-WMO, 2003-09-01, Lodz
11. Pantavou, K., Theoharatos, G., Mavrakis, A. and Santamouris. M. 2011. “Evaluating thermal comfort conditions and health responses during an extremely hot summer in Athens.” Energy Build. 46:339-344.
12. Orosa, J. and Oliveira A.C. 2011. “A new thermal comfort approach comparing adaptive and PMV models.” Renew. Energy 36:951-956.
13. Tseliou, A., Tsiros, I.X., Lykoudis, S. and Nikolopoulou, M. 2010. “An evaluation of three biometeorological indices for human thermal comfort in urban outdoor areas under real climatic conditions.” Build. Environ. 45:1346-1352.
14. Turco, S. H. N., Silva, T. G. F. da, Oliveira, G. M. de, Leitão, M. M. V. B. R., Moura, M. S. B. de, Pinheiro, C. and Padilha, C. V. da S. 2008. Remove from marked Records -Estimating black globe temperature based on meteorological data. Proceedings of the International Conference of Agricultural Engineering, XXXVII Brazilian Congress of Agricultural Engineering, International Livestock Environment Symposium - ILES VIII, Iguassu Falls City, Brazil.

15. The United States Environmental Protection Agency. 2022. The Ultraviolet (UV) Index. https://www.epa.gov/sites/default/files/documents/uviguide.pdf. Access Jan. 20, 2022.
16. Yang, Whui-Ting. 2009. The Characteristics Analysis and Numerical Simulation of Surface Layer UV Index in Taiwan. Master dissertation. Taipei: National Taiwan University, Taiwan.

亞熱帶設施栽培舒適指數評估[1]

陳加忠[2]、陳俊源[3]、陳令錫[4]

摘　　要

亞熱帶地區的設施栽培類型包括遮雨棚、防蟲遮光網室和高隧道設施。高溫，低濕與高日射量影響這些設施內部環境中的作業人員,因此需要確定緩解熱逆境應力的方法。本研究使用量測數據比較三個舒適指數：濕球溫度指數(WBGT)、預測平均指數(PMV) 和紫外線指數(UVI)。在夏季於遮雨棚中所收集有關氣溫、相對濕度、風速、太陽光強度、紫外線能量和作業人員體溫等微氣候數據。以這些量測指標計算三個人體舒適指數。結果顯示所有的紫外線指數都高於安全臨界數值3。WBGT和PMV是設施栽培微氣候下作業人員舒適狀況最相關的指標。使用這些WBGT和PMV指標和其影響因素可以分析改進人員舒適度的方法。使用抗紫外線陽傘降低太陽輻射強度，並使用便攜式風扇加強通風，從而可減輕作業人員的應力。

關鍵詞：舒適指數，預測平均指數，濕球溫度指數，設施栽培

---

[1] 行政院農業委員會臺中區農業改良場研究報告第 1047 號。
[2] 國立中興大學生物產業機電工程學系教授。
[3] 國立中興大學非洲研究中心研究員。
[4] 行政院農業委員會臺中區農業改良場副研究員。