Smart Agricultural Technology 5 (2023) 100319

Contents lists available at ScienceDirect

Smart Agricultural Technology

journal homepage: www.journals.elsevier.com/smart-agricultural-technology

Assessment of health hazards of greenhouse workers considering UV exposure and thermal comfort

Milon Chowdhury, T.M. Abir Ahsan, Md Shamim Ahamed *

Department of Biological and Agricultural Engineering, University of California, Davis, CA 95616-5270, USA

ARTICLE INFO

Keywords:
Greenhouses
Glazing
Shade screen
UV radiation
Heat stress
Thermal comfort

ABSTRACT

Greenhouse (GH) indoor environments are usually manipulated to enhance plant growth and yield, but those environments might not be favorable for GH workers. This study aimed to investigate the health hazards of greenhouse workers from UV radiation exposure and analyze the heat stress and thermal comfort in air-conditioned greenhouses. Two GHs with different covering materials (glass greenhouse-GGH and polycarbonate greenhouse-PCGH) were selected for this study. The UV index of GGH varied from moderate to high (3 to 8) based on the season and deployment of the shade screen, whereas PCGH was always UV risk-free below and above the shade screen. Heat stress was evaluated in terms of wet bulb globe temperature (WBGT) and thermal comfort with the predicted mean vote (PMV) and predicted percent dissatisfied (PPD). The value of WBGT in GGH varied between 17.67 °C and 26.54 °C and between 18.25 °C and 25.97 °C in PCGH. The PMV values ranged from -2.57 to 1.15 for GGH and from -2.24 to 1.42 for PCGH, depending on airspeed, metabolic rate, and indoor conditions. The PPD values ranged between 5.0 to 94.6 % for GGH and 5.0 to 75.0 % for PCGH. As the optimal target range of the indoor environmental parameters (temperature and relative humidity) were maintained in the modern GHs throughout the year, the potential for heat stress and thermal discomfort was not severe. However, as a precaution, avoiding heavy activities around noon is recommended, even in perfectly conditioned greenhouses, which could be above the danger level in low-tech greenhouses.

Introduction

Controlled environment agriculture (CEA) facilities, such as greenhouses, rooftop farms, and indoor vertical farming, could help to expand agricultural operations and increase food production, as the world's population is projected to exceed 10 billion by 2050 [1]. Many fruits and vegetables can be grown in greenhouses throughout the year in any geographical location or climatic condition, with or without active heating and cooling, and it can protect crops from insects and pests and provide a favorable growing environment for maximum yield [2–4]. CEA also offers nutrient-rich produce, minimizes water usage and runoff sustainably, and reduces carbon footprint by shortening the food distribution networks. Greenhouse production still dominates the CEA industries because it leverages natural light for growing crops, and various fruits and vegetables can be grown economically.

Environmental parameters (temperature, humidity, light, and CO_2) in greenhouses must be maintained within the optimal range for plants for high yields and quality products. The spectral composition of light and photoperiod affects plant growth and flowering and fruiting phases. Plants use photosynthetically active radiation (PAR) within 400–700 nm of the solar spectrum. Ultraviolet radiation (UVR, 100–400 nm) is a part (about 5 %) of solar radiation that reaches the earth's surface, which is mainly comprised of UV-A (94 %) [5]. In the past, UVR has generally been considered harmful to crops. Recent studies [6,7] have shown that different levels of UVR can provide several benefits for plants, such as better seed germination, disease resistance, and storage quality of many fruits, vegetables, and ornamental crops. It also influences plants' growth, photosynthesis, and secondary metabolites [8]. UVR is usually divided into three different bands: UV-A (315–400 nm), UV-B (280–315 nm), and UV-C (100–280 nm). The clouds and certain atmospheric gases (e.g., ozone, oxygen, and carbon dioxide) absorb almost all UV-C and about 90 % of the UV-B radiation [9]. A glass or fiberglass-covered greenhouse could receive up to 78 % of incoming UV-A and up to 50 % of UV-B [10]. Most plastic GH coverings come with UV stabilizers that generally block UVR. However, these stabilizers also degrade over time and allow more UVR transmission; UVR transmissivity of untreated plastic films could be up to 78 % [11]. These incoming UVRs, especially UV-A and UV-B, are proven to contribute to cancer risk. UV-A is

* Corresponding author.
E-mail address: mahamed@ucdavis.edu (M.S. Ahamed).

https://doi.org/10.1016/j.atech.2023.100319
Received 26 July 2023; Received in revised form 4 September 2023; Accepted 10 September 2023
Available online 16 September 2023

associated with skin aging, and UV-B is associated with skin burning [12]. Also, overexposure to UVR could cause immune system suppression and eye damage. GH workers might be exposed to UVR for almost an entire year. As the CEA industry expands exponentially, more agricultural workers are involved, and their health risks will increase due to UVR exposure. Several studies were conducted to assess the health risks of outdoor workers, i.e., construction, transportation workers, mail carriers [13,14], farmers [15,16], and mountain guides [17], but the potential risks associated with UVR exposure for GH workers still have not been extensively studied. Greenhouse workers are also unaware of potential UVR exposure and must take preventive action. The first investigation on the UVR exposure of workers in a plastic greenhouse in Almeria reported a maximum ultraviolet index (UVI) of 4.69 in July at noon [18]. They concluded that UVI in the greenhouse exceeded the risk limit (above 3) from May to September.

Solar radiation also directly relates to indoor temperature and humidity levels in greenhouses. The short-wave solar irradiation passes through the transparent roof and is absorbed by the plants and other objects. The heated objects inside the GH radiate longer wavelengths that cannot pass (most greenhouse cover) through the transparent roof and increase the indoor temperature. Although the temperature in greenhouses is maintained at certain set points (15–30 °C) for optimal plant growth, the indoor temperature combined with high humidity, air velocity, types of activities, and clothing isolation may become a critical issue for maintaining the thermal comfort of workers [19]. According to the statistics, outdoor farming workers in the USA suffer heat stroke deaths at a rate nearly 20 times higher than all other workers [20]. An improper thermal environment or heat stress can negatively affect the human body, ranging from discomfort to death. Extensive heat can increase the risk of injuries and discomfort for workers, such as sweaty palms, fogged-up safety glasses, dizziness, heat rashes, heat cramps, heat exhaustion, heat stroke, and even lead to death. The ergonomic-physiological quality of work in the Almeria greenhouse was evaluated for several factors, including physical environment (thermal, light, noise, etc.), workloads, psychological aspects, and working hours. The results indicate that the thermal environment and working hours are the most concerning factors, exceeding danger level 7 out of 10 [21]. A few studies [22–26] evaluated the thermal comfort of workers in low-tech, naturally vented greenhouses. However, limited information is available regarding the thermal comfort of greenhouse workers in well-controlled greenhouses with shade screens. Additionally, the working conditions in closed GHs can be significantly hampered by exposure to pesticides, fungicides, organic dust containing endotoxin, bacteria, allergens, fungi, and gases (CO_2), or other chemical and biological agents, which directly and/or indirectly affect the respiratory system of workers [27,28]. The optimal CO_2 concentration is around 1000–1500 ppm for most crops, and minimal risk exists in greenhouses but may impact worker efficiency at higher concentrations.

The greenhouse industry is exponentially expanding worldwide and is expected to increase with a compound annual growth rate (CAGR) of 9.9 % from 2023 to 2030 [29]. According to the 2012 Census of Agriculture report by the USDA, the number of vegetable and fruit production greenhouses in the USA was 8750 and 573, respectively, which were around half, 4075 and 249, respectively, in 2007 [30]. The US Bureau of Labor Statistics reported about 210,370 workers are involved nationally in crop, nursery, and greenhouse production [31]. The expanding greenhouse industry necessitates robust occupational health and safety guidelines. While existing research focuses on pesticide exposure, ergonomics, and safety equipment, there is a notable research gap concerning UV exposure and thermal comfort in greenhouses.

Greenhouse cover materials are designed to reduce energy consumption while maintaining plant comfort levels, but they may not optimize worker safety from prolonged solar exposure. High-tech, shaded, and mechanically ventilated commercial greenhouses are prevalent and expanding exponentially, but there is no research on potential health risks to workers in these environments, particularly regarding UV exposure and thermal comfort. This study investigates these factors through long-term experiments in two greenhouses resembling high-tech, shaded, and fan-pad ventilated facilities equipped with glass and polycarbonate glazing materials. Experiments were conducted under extreme outdoor conditions to assess worst-case scenarios. Data on solar radiation, UV index, temperature, humidity, and CO_2 concentration were collected using multiple sensors both inside and outside the greenhouses. To evaluate heat stress, Wet Bulb Globe Temperature (WBGT) was employed, and thermal comfort was assessed using Predicted Mean Vote (PMV) and predicted percentage dissatisfied (PPD), utilizing equations and parameters from the ASHRAE handbook. The study concludes with specific recommendations and preventive measures for UVR exposure and thermal comfort levels in greenhouses tailored to the particular greenhouses considered in this investigation.

Materials and methods

Approach for potential health risk assessment

Measurement of UVI

The UV-Index (UVI) was first introduced in Canada in 1992 to make people aware of rising UV levels due to ozone depletion [32]. Later, the World Health Organization (WHO) accepted it and encouraged it to be used as a global standard because it measures UV and suggests how it can affect people [33]. Fig. 1 shows the standard UVI introduced by WHO to take protective measurements from UV as well as create public awareness. Low UVI (1, 2) does not require special protection; workers can safely work under the sunlight. For moderate UVI (3–5), precautions are required, such as wearing a hat and sunglasses, using sunscreen, and staying under shade during mid-day hours. During high UVI (6–7), protection against sun damage is needed by wearing a wide-brimmed hat and sunglass, sunscreen (SPF30+), and wearing long-sleeved shirt and pants. Workers need to reduce their sunlight exposure, especially during mid-day hours. Protection is mandatory under high UVI (8–10 and 11+). Reducing sun exposure is essential, especially from 10 am to 4 pm; full-sleeved clothing, a hat, and sunglasses are necessary, and be sure of sunscreen (SPF30+) and shade. However, many variables, such as human skin, behavior, the length of time spent outdoors, the activity (recreational or occupational), sky conditions, and the location (urban areas, mountains, beaches), affect human exposure to UVR [18].

The International Commission on Illumination (CIE) mentioned a standard process for UVI calculation, where the spectral irradiance produced by the source, hazard weighting coefficient, wavelength interval, and exposure time are the inputs, and the total actinic UV irradiance is the output. Several commercial companies brought UV sensors into the market to avoid calculation complexity, directly providing the UVI value. In this study, the commercial UV sensor (GUVA-S12SD) from *WAVESHARE* was used to measure the UVI, following the application of [34–37].

Approach for heat stress and thermal comfort

Indoor greenhouse environments with elevated temperatures and humidity can affect the cardiovascular and thermoregulatory systems of workers. These conditions adversely affect the productivity, safety, and thermal comfort of greenhouse workers. Many indices, including the wet-bulb globe temperature (WBGT), standard effective temperature (SET), universal thermal climatic index (UTCI), physiological equivalent temperature (PET), predicted mean vote (PMV), and predicted percentage dissatisfied (PPD), are commonly used for analysis the heat stress and thermal comfort of the human being. Each of these indices has its advantages and drawbacks. The WBGT is considered the most accurate measure of heat stress both indoors and outdoors, based on criteria of the American Conference of Governmental Industrial Hygienists and the Occupational Safety and Health Administration (OSHA) Standard [38]. Therefore, we considered the WBGT as a critical parameter to assess the heat stress of greenhouse workers. The recommended WBGT

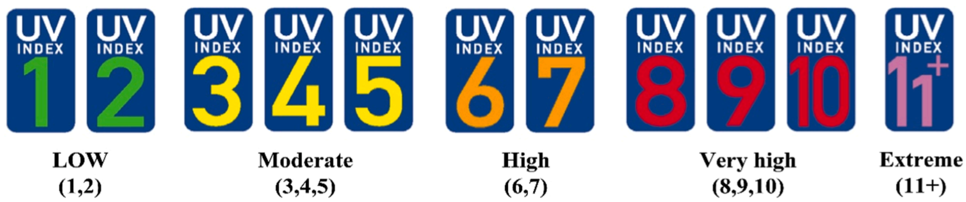


Fig. 1. UV radiation exposure categories and international color codes [33].

could be different (<25–32.5 °C) depending on work types in greenhouses but should not exceed 32.5 °C, and no work is recommended under this situation [23]. The WBGT of greenhouses can be estimated using the correlation proposed by the ISO-7234 standard in the presence of solar radiation [39].

$$WBGT = 0.7 \times T_{nw} + 0.2 \times T_g + 0.1 \times T_d$$

Where T_{nw} is the natural wet bulb temperature (°C), T_g is the globe temperature (°C); and T_d is the dry bulb temperature of indoor air (°C). The globe temperature is calculated using the regression equation [40] formed of solar radiation (SR), air temperature (T_d), and relative humidity (RH).

$$T_g = 0.009624 \times SR + 1.102 \times T_d - 0.00404 \times RH - 2.2776$$

In this study, the natural wet bulb temperature (T_{wb}) is estimated using the following equations [41]:

$$T_{nw} = T_d - C\left(T_d - T_{pw}\right)$$

$$C = 0.96 + 0.069 \log_{10} v \text{ for } v\ 0.03 \le v \le 3.0 m/s$$

The psychrometric wet-bulb temperature (T_{pw}) has been calculated based on ASHRAE recommended Approach in Chapter 1 of AHSRAE fundamental [42]. C is a constant term that is a function of wind speed, v (Fig. 2).

Though WBGT is a well-accepted indicator of heat stress, it is not considered a suitable parameter for thermal comfort analysis. Thermal comfort is a subjective sensation, defined as "the condition of mind which expresses satisfaction with the thermal environment" [39]. A series of indices (UCCI, SET, PET, PMV, PPD) have been developed over time to assess indoor thermal comfort. UTCI, SET, and PET are the most comprehensive indices for calculating heat stress with low humidity and wind speed [43–45]. Besides, SET and UTCI are linked with the reference relative humidity of 50 %, which rarely exists in greenhouses. Greenhouses can be categorized as mixed-mode (MM) buildings, operating under natural ventilation or mechanical conditioning systems. These approaches are highly variable based on the temperature-humidity thresholds required by crops and outdoor conditions. ASHRAE standard 55 recommends treating MM buildings as air-conditioned comfort zones (the standard procedure to calculate thermal comfort is the PMV-PPD model) and abstaining from using the adaptive comfort model regardless of whether or not they are in NV mode. Therefore, we considered the PMV and PPD indices for thermal comfort analysis. PMV value standardizes occupants' sensation about the surrounding environment within certain ranges (−3 to +3), with upper/lower values indicating very hot/very cold and 0 being neutral. Environmental and subjective values (metabolic rate, clothing factor, etc.) are inserted into the PMV model, and the PMV index is calculated. PPD refers to the quantified proportion, expressed in percentage, of individuals who express dissatisfaction with the thermal conditions within their immediate surroundings. A higher PPD value signifies a greater level of discomfort experienced by occupants in the prevailing thermal environment. Fig. 3 shows the relation between PMV and PPD of building occupants. ISO defines the thermal comfort standard with a PMV limit between ±0.5 for new buildings and ±0.7 for existing buildings; however, it can be extendable up to ±2 based on the type of work and appropriate environment (ISO 7730, 2005). The PMV was calculated using four environmental factors (air temperature, radiant temperature, relative air velocity, and relative humidity) and two personal variables (metabolic rate and dynamic clothing insulation factor). The PPD can range from 5 % to 100 %, depending on the calculated PMV. To comply with standards, no occupied point in space should be above 20 % PPD. In this study, PMV and PPD were estimated using *pythermalcomfort,* a Python package developed by the University of California, Berkeley [46] based on the ASHRAE 55 approach [39].

The mean radiant temperature (T_{mrt}) is an important indoor parameter influencing controlled space performance and occupants' thermal comfort. It is used to quantify the exchange of radiant heat between a human and their surrounding environment. Generally, the number of occupants per greenhouse area unit is lower than the commercial and residential buildings [47,48]. Also, the ASHRAE handbook [42] and European Guidebook [49] stated that mean radiant

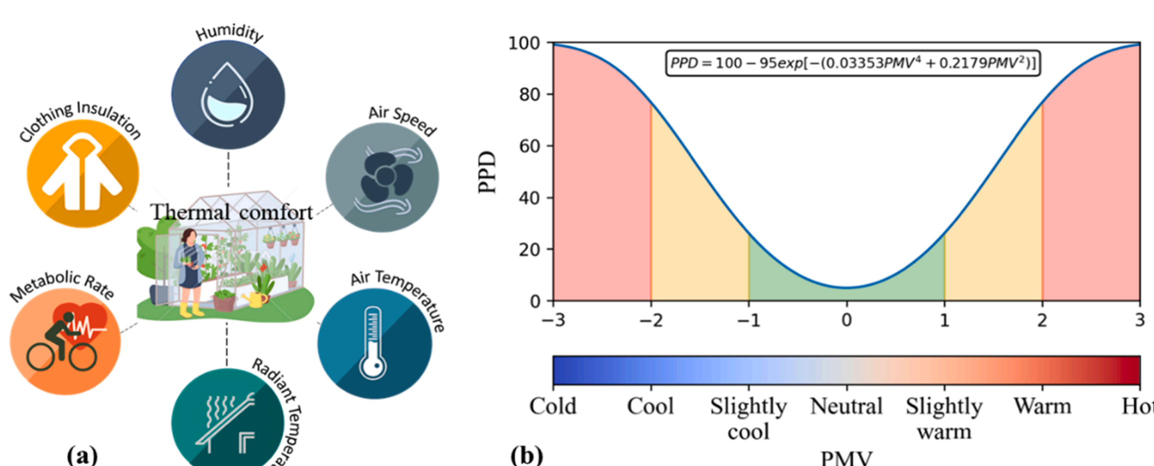


Fig. 2. (a) Factors linked with PMV and (b) Graphical interpretation of the relation between PMV and PPD.

Fig. 3. Experimental site: (a) location of the GHs, (b) GGH, and (c) PCGH.

temperature has an approximately equal effect on thermal comfort, like room temperature, and other studies [50–52] also reported minimal difference between mean radiant temperature and indoor air temperature. Therefore, we considered the mean radiant temperature (T_{mrt}) equal to the indoor air temperature (T_i). The possible extreme limits (max and min) of other related input variables (air velocity and metabolic rate) were selected to evaluate the thermal comfort variation of GH workers since air speeds vary dynamically based on ventilation fan control and metabolic rates vary based on activity levels of different stages of the plant growth cycle. The airspeed, clothing insulation factor, and metabolic rate were considered based on possible extreme reported values of 0.2 and 0.75 m/s [53] and 1.3 and 3.3 met [54], respectively. In the *pythermalcomfort* package, the dynamic clothing factor is used to estimate the PMV and PPD value, which is changed based on the clothing insulation factor (clo) and metabolic rate (met). Similarly, the package considers the relative wind velocity for estimating the PMV and PDD.

Overview of the experimental greenhouses

The experiment was conducted in two separate Venlo-style greenhouses, glass-covered and polycarbonate-covered (Fig. 1), in the core greenhouse facility at the University of California, Davis (Latitude: 38.55°N and 121.75°W). Bell pepper plants were grown in the glass greenhouse (GGH), and Cocoa trees in the polycarbonate greenhouse (PCGH). The properties of the GGH and PCGH are summarized in Table 1. The structure of both GHs was made of galvanized steel and integrated with the shade screen (61 % Polyester + 39 % Aluminum). The shade screen in the GGH was controlled dynamically based on solar radiation, as shown in Table 2, whereas the PCGH shade screen was always deployed. The ambient temperature and humidity of both GHs were maintained using an evaporative fan-pad cooling system. The cooling pads were installed laterally in the GGH and longitudinally in the PCGH, as shown in Fig. 4 (b and c).

Table 1
Properties of the experimental greenhouses (GGH and PCGH).

Parameters	GGH	PCGH
Gutter height (m)	3.66	4.25
Ridge height (m)	4.57	6.83
Length × width (m)	7.30 × 9.14	44.20 × 20.12
Floor area (m^2)	66.81	889.30
Floor material	Concrete	Concrete
Covering material	Tempered glass	Twin polycarbonate
Thickness (mm)	6[a]	6[b]
Light Transmission (%)	80[a]	82[b]
UV transmission of cover (%)	4[a]	Almost opaque[b]
Shading material	TEMPA 5557 D FB (61 % Polyester + 39 % Aluminum)[c]	
Shading in beam, PAR (%)	55[c]	
Shading in diffused, PAR (%)	61[c]	
UV transmission of shading (%)	8[c]	
Temp-humidity control	Evaporative fan-pad cooling	

[a] Tempered Glass IQ [55].
[b] Verolite™ 6 mm Polycarbonate sheet [56].
[c] TEMPA 5557 D [57].

Table 2
Thermal shade screen control strategy of the GGH.

Outdoor solar radiation (W/m^2)	< 600	600–799	800–899	900–1000	>1000
Opening of the screen (%)	100	75	50	25	0

Data acquisition system

This study measured indoor solar radiation, UVI, temperature, humidity, and CO_2 concentration to assess the potential health risks and thermal comfort of greenhouse workers. A total of six sensor nodes were prepared for each GH, where three nodes were placed around 1.8 m above the floor (average Americans' height [58], including the ankle position about 5 inches above the floor and the hand's location above the floor), and the other three nodes were placed above the thermal shade screen (around 4 m and 5 m above the floor of the GGH and PCGH, respectively). To accurately quantify the health impacts of human exposure to growing conditions inside a greenhouse, it has been deemed appropriate to consider the placement of sensors at the height of an average American during standing conditions. This decision is based on the observation that greenhouse workers typically work standing. Fig. 4 shows the overall data acquisition process and sensor locations of this study.

Each node contained one temperature-humidity sensor and one UVI sensor. As direct and prolonged exposure to strong sunlight degrades the temperature-humidity sensor's performance, a shading plate was attached above each temperature-humidity sensor. Solar radiation, air velocity, and CO_2 sensors were connected additionally to the middle sensor node under the shade screen (Node 5). A total of fifteen sensors (six temperature-humidity, six UVI, one solar radiation, one air velocity, and one CO_2) were connected to the Raspberry Pi. The digital temperature-humidity sensors were connected directly, and analog sensors were connected to the Raspberry Pi through the analog-to-digital converter (ADC) device. All sensors were calibrated according to the standard calibration methods; for example, temperature and humidity levels were calibrated by comparing them to a reference thermometer [59] and saturated salt solutions [60]. The UV sensors were calibrated using a known UV light source (352–365 nm UV lamp, which resulted in 15 UVI), and the CO_2 sensor was calibrated following the instructions mentioned by the manufacturer (by short-circuiting the HD and GND pins of the sensor). The outdoor environmental data for similar parameters were collected from the Argus weather station installed next to the GHs at the UC Davis core greenhouse facility. A separate UV

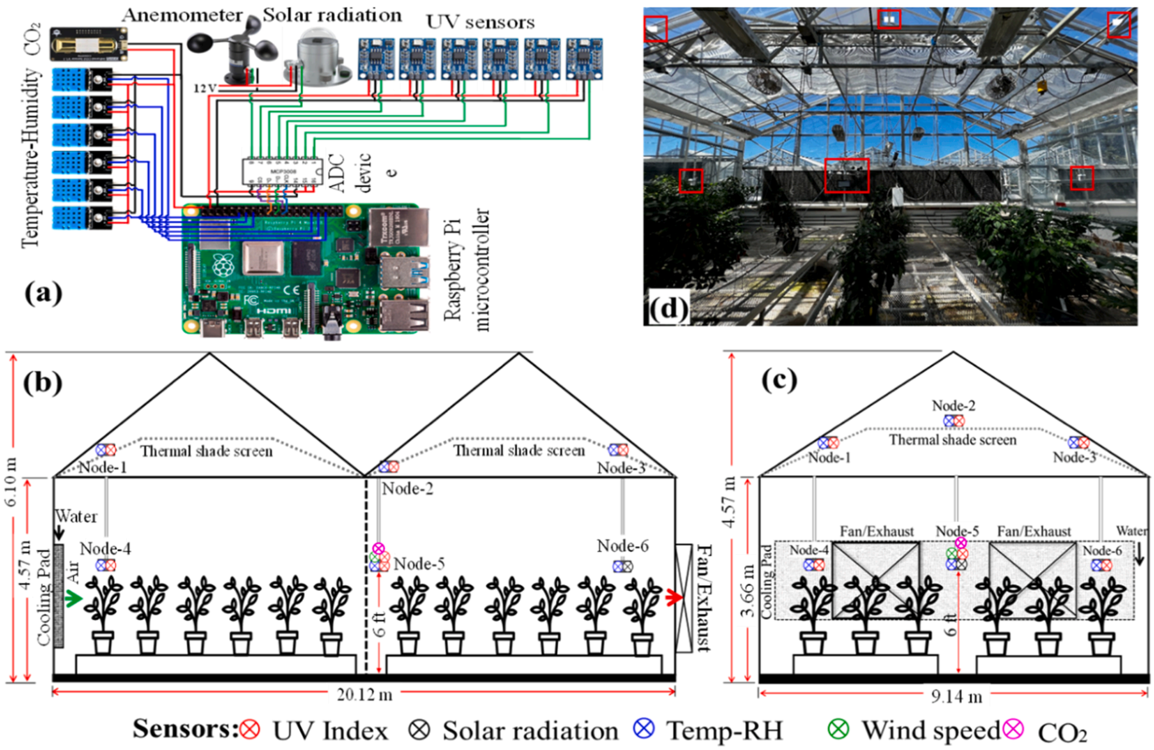


Fig. 4. Overall data acquisition system of this study: (a) circuit diagram of the data acquisition system (DAQ), (b) position of sensor nodes in the PCGH (multi-span), (c) position of sensor nodes in the GGH, and (d) indoor condition and sensor location of the GGH.

sensor was installed outside the GH on August 19, as the Argus system had no UVI measurement device. The CO_2 sensors were added on the same day to measure the indoor CO_2 concentration. The specifications of each sensor and microcontroller are summarized in Table 3.

Data analysis

The data acquisition process spanned from July 12 to September 20, 2022, during which the collected data was categorized into two distinct segments: the summer season data encompassing the period from July 12 to August 31 and the fall season data covering September 1 to 20. The latter portion of the fall season was deemed less crucial for evaluating thermal comfort and, thus, not essential for further analysis. Given the nature of the greenhouse as a solar collector throughout the year, particularly in regions like California where solar heat gain is notably high, conducting experiments during the peak summer period was deemed appropriate. However, the initial phase of the fall season was included in the data collection as solar radiation remains relatively high during this period, gradually diminishing as summer transitions into fall. As the cloud is an atmospheric component that significantly impacts solar intensity on the earth's surface, the cloud factor was also considered during the data analysis. According to the Okta-based cloud factor (CF), 0 indicates a clear sky, and 8 oktas are an overcast sky, respectively [61,62]. One cloudy or partly cloudy and one clear sky day were selected from the summer and fall season data to show the variation of solar radiation, UV index, temperature, humidity, heat stress, and thermal comfort level. CF data was not available for the study location, so the fractional CF was determined from the ratio of actual (measured) to clear-sky solar radiation data from the National Solar Radiation Database (NSRDB), as mentioned by [63] and converted into CF percentage. Later, the CF was converted into the okta index; for example, if 50 percent of the sky is covered, since 100/8 = 12.5, dividing 50 by 12.5 resulted in 4 oktas. For detailed analysis, we have considered one clear day and one partly cloudy day from the summer and fall seasons, as shown in Table 4.

All raw data were collected at every 15-second interval. The data were pre-processed to remove the outliers and then conduct the uncertainty analysis. The first and third quartile, interquartile range, and upper and lower bound were calculated to remove the noise and outliers. Then, the hourly average and standard deviation of the recorded data were calculated. Moreover, data recorded by several nodes were also averaged, such as temperature, humidity, and UVI data measured by sensor nodes 1, 2, and 3 (above shade screen), and nodes 4, 5, and 6 (under shade screen) were averaged. Due to unpredictable factors while conducting any experiment, the data collected throughout the study may sometimes differ from the actual value. The errors in any experimental dataset are typically related to the bias error (B_x) and random error (R_x) [64]. This study separately estimates the bias and random errors and combines them using the following equation [65].

$$U_x = \sqrt{B_x^2 + R_x^2} = \sqrt{B_x^2 + \left(\frac{ZS_x}{\sqrt{n}}\right)}$$

where Z = 2 for 95.5 % confidence that the values are within $\pm 2 \cdot S_x$ of the mean; S_x is the standard deviation, and n is the number of data points. The measurement uncertainty of the considered variables of this study is shown in Table 5.

Results and discussion

Potential exposure to UVR

Solar radiation is a critical parameter for maintaining the optimal growing environment for plants. Cloud factors, air pollution, location, and the time of the year are responsible for the variations in solar radiance at the Earth's surface, ultimately inside the greenhouse. Besides this, GH-covering materials and shade screens also affect solar radiation's intensity and solar spectrum inside. The amount or availability of solar radiation to the plants is comparatively lower than in the outdoor environment based on the transmissivity of covers. Fig. 5

Table 3
Specifications of the data acquisition system components.

Item	Model	Image	Specification
Ultraviolet Ray Module	GUVA-S12SD		Measuring range: 240–370 nm Measuring accuracy: ±1 UVI Response time: 0.5 s Operating temperature:–20–85 °C Power supply: 3.3–5 V DC
Temperature-Humidity Sensor	DHT-11		Meas. range: 20–90 % RH, 0–50 °C temp. Accuracy: ±5.0 % RH, ±2.0 °C temp. Resolution: 1.0 % RH, 1.0 °C temp. Power supply: 3.3–5.5 V DC
Solar Radiation Sensor	RS-RA-30AL		Measuring range: 0–1800 W/m^2 Annual stability: ≤ ±2 % Resolution:1.0 W/m^2 Power supply: 10–30 V DC Output: 4–20 mA, 0–10 V DC
Wind Speed Sensor	WSS-1		Measuring range: 0 to 45 m/s Accuracy: ± 0.3 m/s Resolution: 0.1 m/s Start Air velocity: ≤0.5 m/s Power supply: 12–24 V DC
Infrared CO_2 Sensor	SEN0219		Measuring range: 400–5000 ppm Accuracy: ± 100 ppm Resolution: 1 ppm Lifespan: >5 years Power supply: 5 V DC
Raspberry Pi Module	Raspberry Pi 4 Model B (8GB)		Broadcom BCM2711, Quad-core Cortex-A72 (ARM v8) 64-bit SoC @ 1.5 GHz 8GB LPDDR4–3200 SDRAM 2. 4 GHz and 5. 0 GHz IEEE 802. 11B/g/n/ac Wireless LAN, Bluetooth 5. 0, double-true Gigabit Ethernet

Table 4
Considered days for assessing the health hazards in GGH and PCGH.

Season	Sky condition	Cloud factor	Date
Summer	Sunny	0	July 17, 2022
	Partly cloudy	4	August 1, 2022
Fall	Sunny	0	September 2, 2022
	Partly cloudy	3	September 18, 2022

Table 5
Uncertainty analysis of the sensors used in this study.

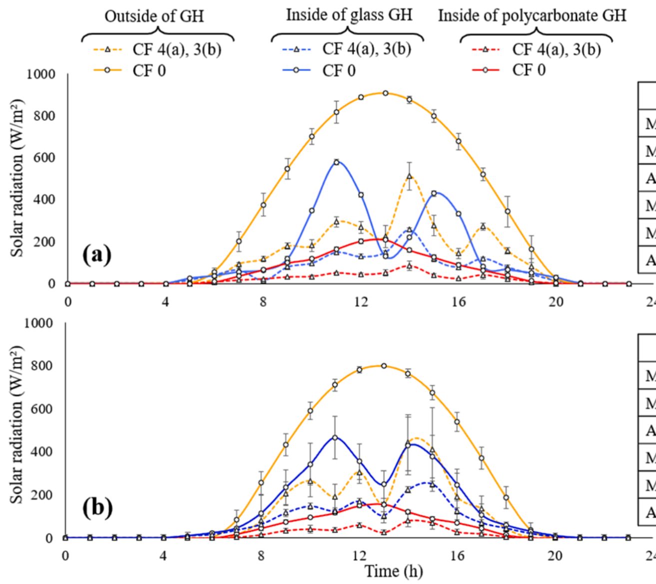
Measured parameter	Standard deviation	Bias error (B_x)	Random error (R_x)	Overall uncertainty (U_x)
UV Index	0.85	1.00	0.17	1.17
Temperature (°C)	2.89	2.00	0.59	2.09
Humidity (%)	2.91	5.00	0.60	5.04
CO_2 (ppm)	1.72	6.00	0.35	6.35
Radiation (W/m^2)	67.38	3.00	13.75	14.07

compares the outdoor and indoor solar radiation of the GGH and PCGH, considering the CF and season factors along with the maximum, minimum, and average solar radiation and temperature of those days.

A significant difference in solar radiation was observed due to the CF for the selected summer and fall days. In the case of CF 0 (clear day), a perfect bell-shaped pattern is noticed for the outdoor and PCGH. However, an abrupt fluctuation can be seen in the GGH graphic due to the off/on deployment of the thermal shade screen between 10.0 and 4.0 pm. On the other hand, a fluctuation of solar radiation was observed for the partially cloudy days (4-summer and 3-fall) based on the variation of CF; a similar graphic pattern was observed for the representative days of summer and fall sessions. The measured solar radiation inside the GGH was 30 % less than the outdoor radiation when the thermal screen was deployed. About 75 % less solar radiation was measured inside the PCGH, which is the combined impact of the solar transmissivity of the cover and shade screen.

The observed UV index inside the GH was lower compared to the outside value, which varies largely depending on the radiometric properties of the cover. Fig. 6 shows the variation of outdoor and average indoor (above and under the screen) UVI for a typical clear day in the summer (6a) and fall (6b) seasons. As polycarbonate reflected most UVR, the inside UVI was almost negligible for both seasons. For GGH, the above-screen UVI reached 8.0 at noon when the outside value was 15.0, whereas the maximum UVI was 4.0 under the screen. The UVI value under the screen fluctuated based on the opening and deployment of the screen. The canopy area UVI values were similar to those above the screen in the early morning and late evening when the screen was not deployed. The standard deviation of the hourly UVI measured under the shade screen in GGH was higher in summer (6a) as the shade screen deployed and frequently un-deployed from maintaining the target light intensity. In contrast, the movement of the shade screen was lower in the fall, which decreased the standard deviation of the hourly UVI (6b). The UVI was generally within the moderate (3–5) or safe (1–2) ranges under the screen, even on a clear day at noon.

Fig. 7 shows the variation of the UVI due to the seasons and CF, where 7(a) and 7(b) indicate the UVI from the six sensor nodes (nodes 1–3 located above and 4–6 under the shade screen) of the GGH and PCGH. As expected, deploying the shade screen and CF significantly reduced the UVR exposure in the greenhouses. Like for clear days, the UVI values are almost negligible for the PCGH, even above the screen. In contrast, they exceed the danger level (6–7) above the thermal screen with a maximum value of 8.5 and moderate (3–5) with a maximum value of 5.3 below the screen for a clear day in GGH. The UVI was relatively low for node-2 (middle) because of having an additional screen under the roof vent. However, the UVI values below the screen were within the safe range (below 3) for the partially cloudy (CF 4 and 3) days in both seasons. Also, some variations between nodes were caused by surface azimuth and the change in solar altitude angles based on the position of sensors in the greenhouses. These patterns could significantly differ for other locations as the UVI varies with the geological locations. For example, GHs at higher elevations receive more UVR, which declines if GHs are far from the equator [66]. The high errors were mostly observed in GGH, where the shade screen opened and closed more



Parameter	0 CF	4 CF
Max. rad (W/m²)	877.00	637.00
Min. rad (W/m²)	0.00	0.00
Avg. rad (W/m²)	310.43	118.10
Max. temp. (°C)	40.61	30.22
Min. temp. (°C)	16.06	17.22
Avg. temp. (°C)	27.89	23.21

Parameter	0 CF	3 CF
Max. rad (W/m²)	804.00	761.00
Min. rad (W/m²)	0.00	0.00
Avg. rad (W/m²)	259.89	102.19
Max. temp. (°C)	39.83	24.44
Min. temp. (°C)	16.78	15.28
Avg. temp. (°C)	26.31	17.73

Fig. 5. Comparison of solar radiation for the typical representative clear and partially clouded day: (a) summer season and (b) fall season.

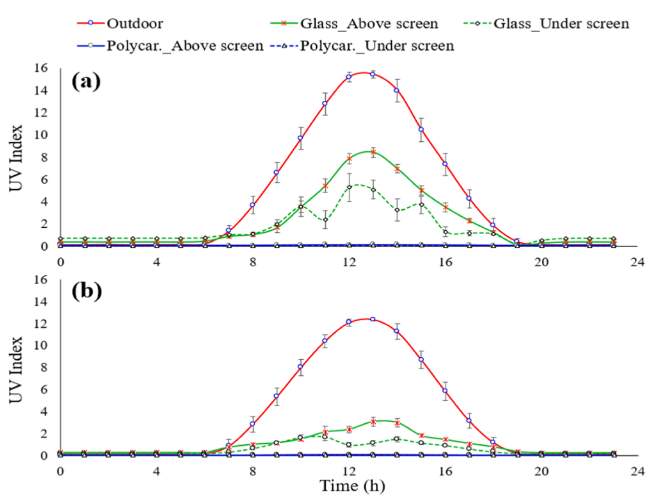


Fig. 6. The comparison of outdoor UVI with averaged indoor UVI (above and under the shade screen) of the GGH and PCGH: (a) summer season and (b) fall season.

frequently and around noon when temperature and solar radiation fluctuated with large numbers based on cloud coverage.

Overall, the UVI of GGH varied from moderate to high (3 to 8) based on the season and deployment of the shade screen. The PCGH was always UV risk-free below and above the shade screen due to the low UVR transmission properties of polycarbonates. According to the specification of the tempered glass, it usually transmits 4 % of UVR; however, we found around 55 % transmission of the UVR, which could be due to the property degradation from aging (about 20 years). Also, it was reported that the shade screen transmits 8 % of the UVR; it practically transmits more than that percentage. There are a few specific studies about the performance degradation of thermal shade screens, specifically TEMPA 5557 (radiation-control screen system). One study reported that the instability of shade screen properties due to dust accumulation, long-term exposure, and abrasion could significantly change the energy flux exchange [67]. The results indicate the risk from UVR could be substantially minimized (up to 78.8 % for GGH and 99 % for PCGH) by using the cover with low UVR transmissivity and deploying a shade screen under high radiation conditions.

Heat stress and thermal comfort

Heat stress and thermal comfort are the perceptions of humans about the variation of temperature, solar radiation, relative humidity, and air velocity around their bodies. Fig. 8 shows the variation of measured outdoor air temperature and indoor (above and under shade screen) temperature in GGH (8a) and PCGH (8b) regarding the season (summer and fall) and CF factor (clear sky and partially cloudy days). The indoor temperature (bellow screen) of PCGH was slightly higher in the daytime than in GGH. The maximum temperature in PCGH was recorded up to 30 °C in summer under the clear sky, whereas less than 25 °C in GGH. The temperature above the shade screen was very high (around 70 °C at noon) due to the heat buffer and the solar radiation reflection from the shade screen, and also no active cooling like the below screen. For the same reasons, the effect of could cover on temperature variation above the shade was prominent (up to 20 °C), while it was modest underneath the shade screen due to active cooling. Compared to the inside temperature of the GHs, the outdoor temperature was lower at night and higher during the daytime. It increased with the intensity of sunlight but took time to drop down. A similar trend of indoor temperature fluctuation was observed in both greenhouses as the evaporative cooling system operated based on the same control logic.

Fig. 9 shows the variation of measured relative humidity inside and outside the greenhouse, considering similar factors like temperature (Fig. 8). Although there was no target range, the relative humidity varied between 50 and 87 % in PCGH; as expected, the RH was significantly higher at night due to reduced ventilation. In GGH, the RH ranged between 57 and 87 %, but there was no significant difference over the days. This difference in RH in GGH could be because of higher transpiration from pepper and more water addition from the evaporative cooling system. The high RH under partially cloudy conditions was caused by reduced ventilation and relatively low indoor temperature. The outside and the above screen RH decreased with the air temperature increase. Similar patterns were also found under the clear sky except at mid-day (almost zero from 12 am to 5 pm) when the humidity sensors stopped working as the air temperature exceeded the optimal operating conditions (50 °C).

Fig. 10 shows the daily variation of WBGT in the greenhouses for selected days in summer and fall under two different airspeeds. The airspeed change from 0.2 to 0.75 m/s has a minimal impact on the WBGT, but WBGT slightly decreased with the airspeed increase. The WBGT follows a similar trend of indoor air temperature, which increases

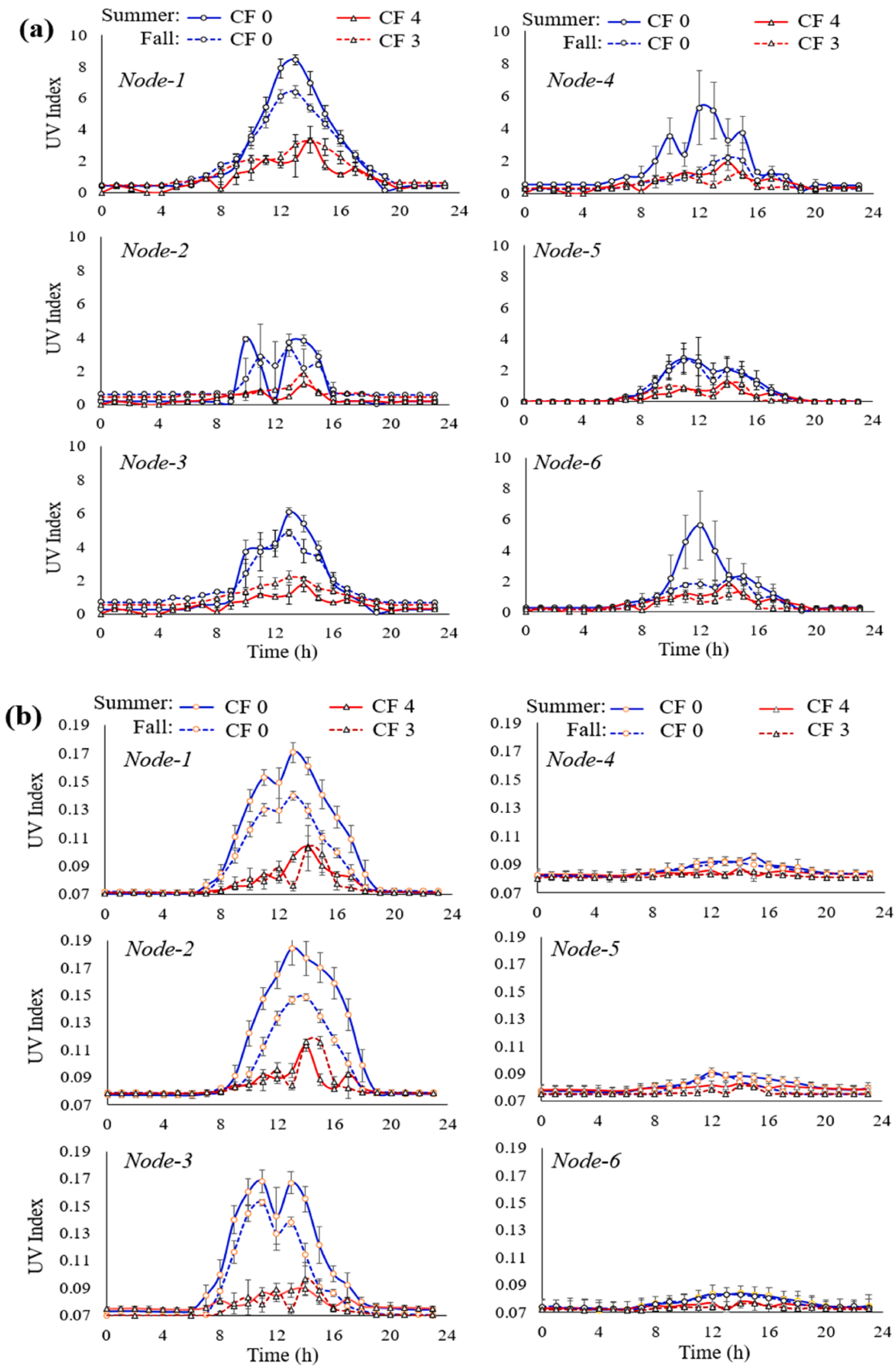


Fig. 7. Variation of UVI due to season and CF for different sensor nodes: (a) GGH, (b) PCGH.

after sunrise and reaches a peak value at around noon. The difference between the WBGT and the indoor air temperature ranged between 1.0–4.5 °C; the highest difference was observed in PCGH. The average value of WBGT in GGH varied between 17.67 °C and 26.54 °C and between 18.25 °C and 25.97 °C in PCGH. Based on the temperature profile (Fig. 8), the PCGH daytime temperature was higher (max difference 7.1 °C) than GGH but a relatively low RH in PCGH (Fig. 9); ultimately, the hourly WBGT in PCGH was mostly lower than GGH. However, the peak value of temperature, RH, and solar radiation did not coincide, but the change in indoor temperature seems to have a more significant impact on WBGT as it follows an almost similar trend with indoor temperature.

In general, the WBGT in the greenhouses never touched the critical level (above 32.5 °C, no activity) but rarely exceeded 25 °C, above which some heavy greenhouse activities are not recommended, which was around 25 °C for both greenhouses from 10.0 am to 4.0 pm in summer under the clear sky. It can be concluded that the potential for heat stress is very minimal in a highly controlled greenhouse with active cooling and ventilation systems. Finally, it should be noted that WBGT is the most commonly used parameter for heat stress analysis, but the

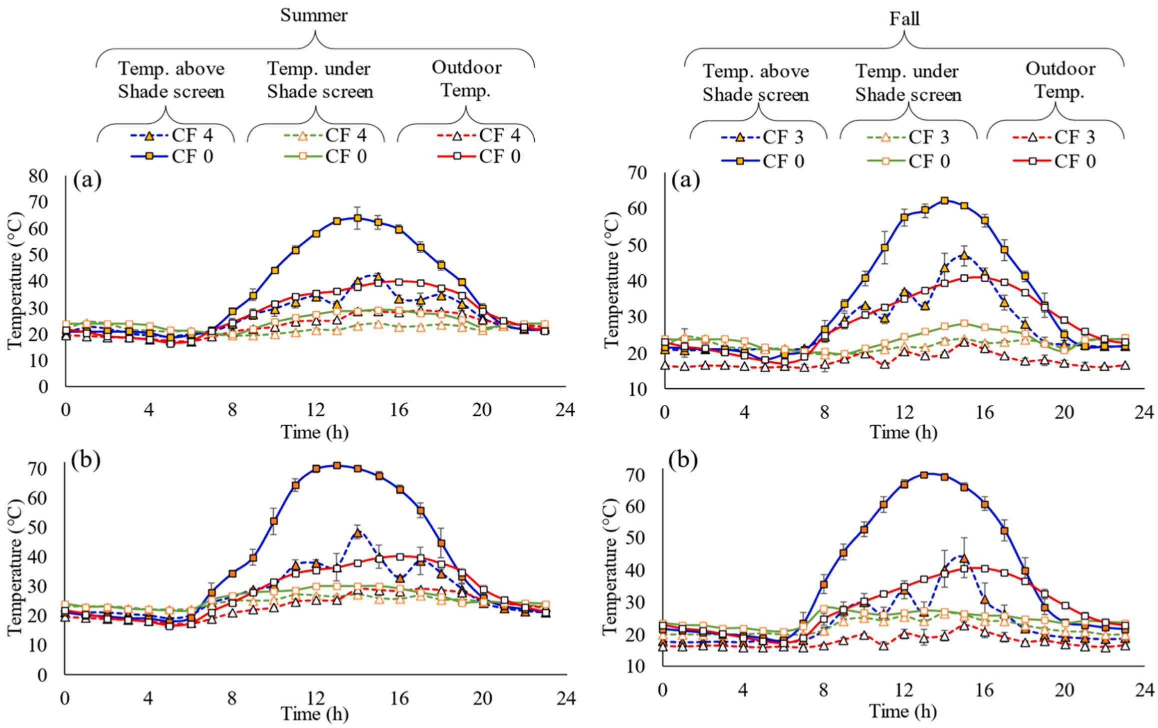


Fig. 8. Indoor and outdoor temperature variation of the (a) GGH and (b) PCGH due to thermal shade screen and season for a typical clear and partially cloudy day.

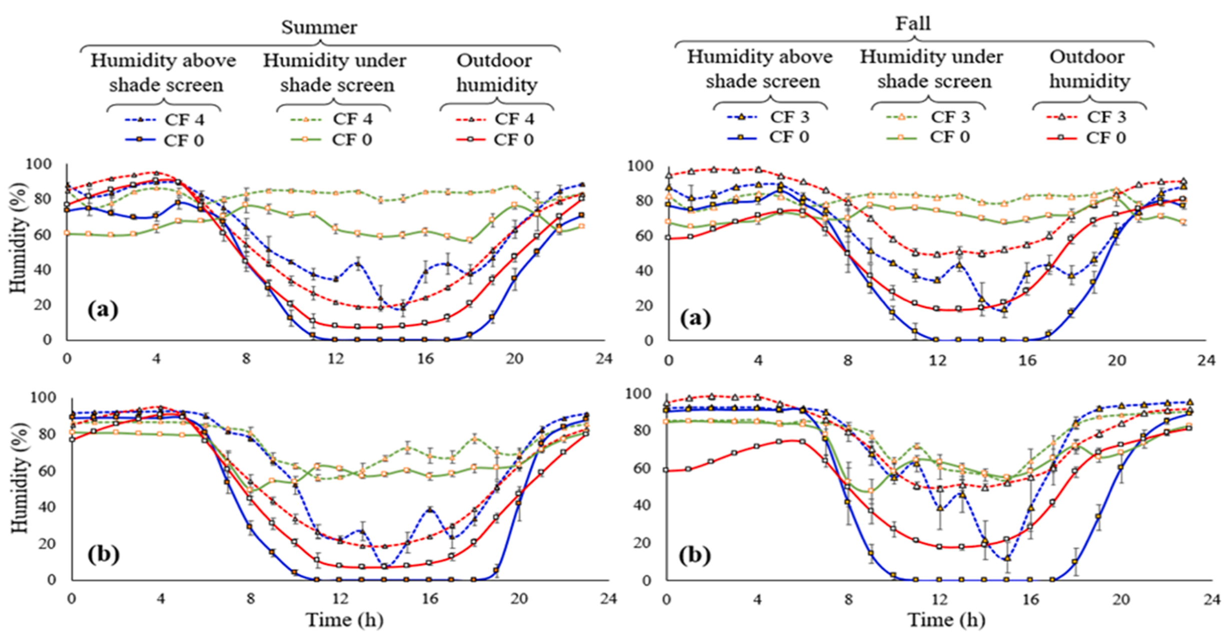


Fig. 9. Indoor and outdoor humidity variation of the (a) GGH and (b) PCGH due to the thermal shade screen and season for a typical clear and partially cloudy day.

conclusion could be less reliable with high RH and less air movement than outside [68], like in greenhouses. The humidity index provides reliable results for higher temperatures but does not consider the effect of wind and solar radiation [69]. In the future, more investigation is critical for developing the appropriate parameters for heart stress analysis in greenhouses.

The indoor temperature and humidity are not the only factors determining thermal comfort. PMV and PPD are commonly used to assess the thermal comfort of building occupants under controlled or mechanical cooling [70]. Most commercial greenhouses are operated like buildings with precision control of temperature and humidity, so PMV and PPD were considered prime parameters for thermal comfort analysis in this study. Figs. 11 and 12 shows the calculated PMV and PPD values in GGH and PCGH for the selected days in summer and fall with factors including cloudiness, airspeed, metabolic rate, and clothing insulation. The PMV values ranged from −2.57 to 1.15 for GGH and from −2.24 to 1.42 for PCGH, depending on airspeed and other factors. Similarly, the PPD values ranged between 5.0 to 94.6 % for GGH and 5.0 to 75 % for PCGH. As expected, the PMV and PPD indicate similar outcomes in terms of thermal comfort for both greenhouses. In most cases, the thermal comfort was related to cold sensations, especially at night when greenhouses usually have no occupancy. The hot sensation

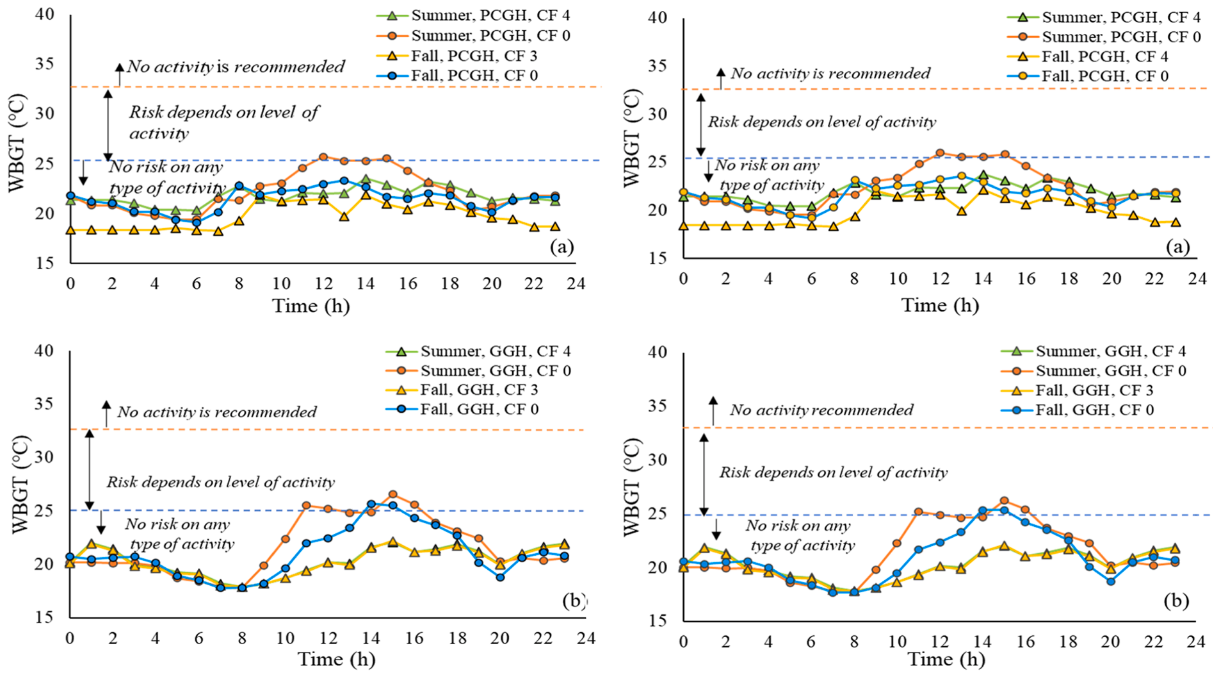


Fig. 10. Daily variation of WBGT in (a) GGH and (b) PCGG for the selected day of summer and fall with two different airspeeds (left: 0.2 m/s and right: 0.75 m/s).

was only found for medium to heavy work (metabolic rate 3.3 met) around noon under a clear sky in summer, especially for PCGH. The impact of airspeed is more prominent for cold sensations in the early morning and late evening. The cold sensation and PDD can be significantly decreased by changing the activities from normal (1.3 met) to heavy work (3.3 met).

In GGH, the lowest cold sensation (PMV) and highest PPD were observed at around 8.0 am, whereas at around 6.0 am for PCGH. This could be due to operating the ventilation system for humidity control in the early morning or the activation of evaporative cooling in GGH. The lowest indoor temperature (19.8 °C) and WBGT (17.7 °C) in the GGH were also found during that time, which also justified the reason for having low thermal comfort at 8.0 am after two hours of sunrise. A few inconsistent results are noticed in GGH, possibly due to the dynamic operation of the shade screen. It is generally recommended to perform heavy work during the early morning and late evening and light work during the middle of the day to experience better thermal comfort in greenhouses. However, if the greenhouse temperature and humidity are not properly controlled especially for low-tech greenhouses, then thermal comfort could be a critical issue for the workers. Based on the results presented above, it can be concluded that the thermal comfort of greenhouse workers could be significantly different depending on several factors, especially indoor temperature, humidity, and clothing factors. If the indoor temperature is maintained within 20–24 °C and relatively low RH, then thermal comfort will not be a critical issue for greenhouse workers.

In this study, we considered a single clothing factor (0.5 clo) as most commercial greenhouse workers used standard dress codes, like full sleeves aprons; the results could be significantly different based on different clothing configurations. It is also worth mentioning that a PMV and PPD-based analysis of thermal comfort performs better in properly conditioned greenhouses than in naturally ventilated greenhouses. The adaptive model is recommended to analyze the thermal comfort of naturally ventilated spaces like low-tech greenhouses [71,72]. Indoor air quality is also an essential factor for thermal comfort and safety for the occupants. In general, CO_2 is not a major concern for greenhouse workers as the indoor concentration never exceeds the permissible exposure limit (PEL) by ASHRAE (1000 ppm) and OSHA (5000 ppm). Fig. 13 shows the seasonal variation of CO_2 concentration inside the GGH and PCGH without artificial CO_2 supplementation. The measured CO_2 concentration was almost similar to the normal outdoor value during the daytime (8 am to 6 pm) as the evaporative cooling system was mostly in operation, or the ventilation system was kept on for dehumidification. The GH workers' working hours (8 am to 5 pm) are between this period. The CO_2 concentration gradually increased from the evening and peaked before sunrise. Similar outcomes were observed in another study [73], where CO_2 concentration was around 420 ppm in the daytime and about 600 ppm at night. The measured CO_2 concentration in the fall season is higher than in the summer. It could be from a possible low photosynthesis rate in the fall due to the low intensity of solar radiation [74,75]. The CO_2 concentration of the PCGH was higher than the GGH due to respiration at night because the number and growth stage of Cocoa plants were prominent compared to the pepper plants of the GGH. In the future, it might be critical to investigate the impact of high CO_2 concentration from artificial supplementation on worker performance, especially in cannabis production.

Indoor thermal comfort and air quality assessment have been a global concern for many years, as most people spend up to 90 % of their time indoors due to their jobs or other personal activities [76–78]. The indoor air quality of the GHs is rarely assessed and maintained because plants are prime targets for optimal environmental management. As the CEA industry is growing, a few studies focus on GH workers' thermal comfort, and there are no specific ISO standards for this industry. This study's results were interpreted as compared with other sectors with a similar working environment [79–81]. More studies and guidelines are critical for ensuring the safety and well-being of indoor farming workers.

Conclusions and recommendations

This study focused on GH workers' health hazards due to UV exposure and the thermal comforts inside the greenhouses. Data was collected considering different factors (e.g., types of GH covering materials, shade screen operation, CF, and season), and obtained results were compared with the ISO, ASHRAE, and other relevant standards. According to the results obtained from the UVI, heat stress, and thermal comfort, the conditions with horticultural GGH workers might have some health risks related to UV radiation due to the degradation of covering material properties and operation strategies of the shade

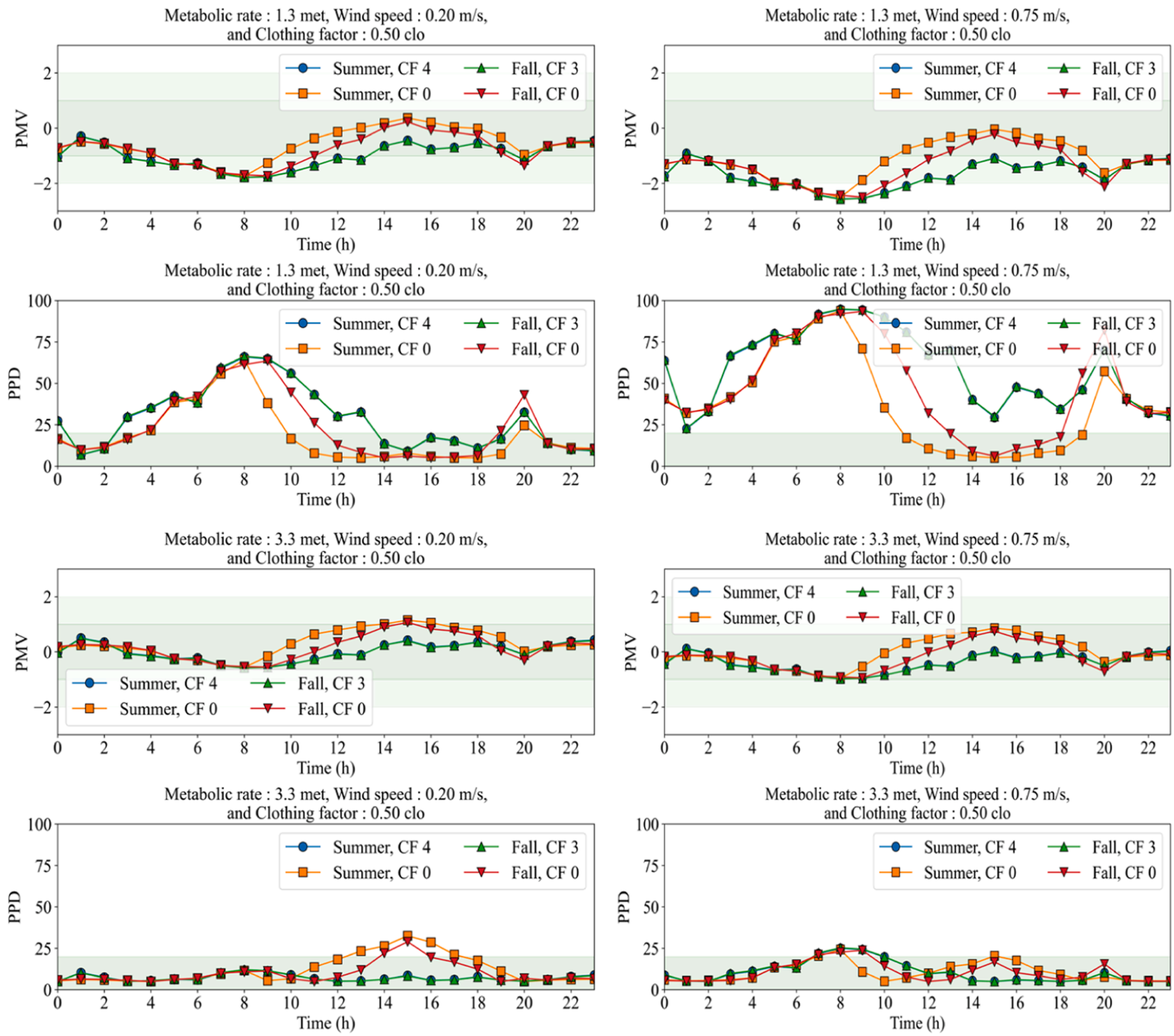


Fig. 11. PMV and PPD values of GGH under summer and fall with different factors (cloud cover, metabolic rate, clothing factor, and airspeed).

screen. In summer, the UVI value in GGH ranged between 3 and 8 depending on the operation of the shade screen, whereas UVI in PCGH was negligible even above the shade screen. The indoor environment in GGH was generally less comfortable than the PCGH due to the variation of indoor environmental parameters related to the property of covering materials, efficiency of environment control systems, and plant density. The WBGT in GGH varied between 17.67 °C and 26.54 °C and between 18.25 °C and 25.97 °C in PCGH. The PMV values ranged from −2.57 to 1.15 for GGH and from −2.24 to 1.42 for PCGH, depending on airspeed, metabolic rate, and indoor conditions, whereas the PPD values ranged between 5.0 to 94.6 % for GGH and 5.0 to 75.0 % for PCGH. The PPD value exceeded the recommended 20 % range mostly because of cold sensation and sometimes from hot sensation at around noon at clothing insulation of 0.5 clo.

This study was conducted in a fully controlled environment, specifically an air-conditioned greenhouse with a shade screen. The results and findings of the study may not be directly applicable to low-tech or unconditioned greenhouses, which may not have the same level of environmental control. Additionally, the aging of the greenhouse cover and shade screen could affect the accuracy of the results as well. Therefore, having some standards and guidelines for indoor farming systems is also critical from the worker's perspective. The outcomes from this study would be critical components for future research and development related to safety, heat stress, worker performance, and thermal comfort analysis of greenhouse workers and the development of greenhouse worker safety measures and guidelines. The following are the general recommendations for protective measures and future research:

➢ UV exposure can pose risks to workers in glass greenhouses, even when shade screens are deployed, particularly at higher UVI levels (6–8). It is worth noting that the installation of shade screens in greenhouses is primarily driven by energy efficiency concerns rather than health considerations. Energy efficiency-driven control strategies may not prioritize the health and well-being of workers. However, this is not the case with polycarbonate greenhouses, as polycarbonate covers offer greater opacity to UVR than other materials, such as low-density polyethylene (LDPE). Furthermore, applying UV stabilizers in polycarbonate enhances its resistance to photodegradation, enabling it to maintain its UV resistance over prolonged periods, even under high temperatures. However, it is important to note that the performance of another commonly used greenhouse covering material (LDPE) under similar considerations has not been investigated in this study. Future research should assess LDPE's performance in terms of UV protection. The existing greenhouse monitoring systems do not directly measure the UVI. Therefore, it is recommended that regulatory bodies enforce the monitoring of the UVI and ensure workers are informed about their

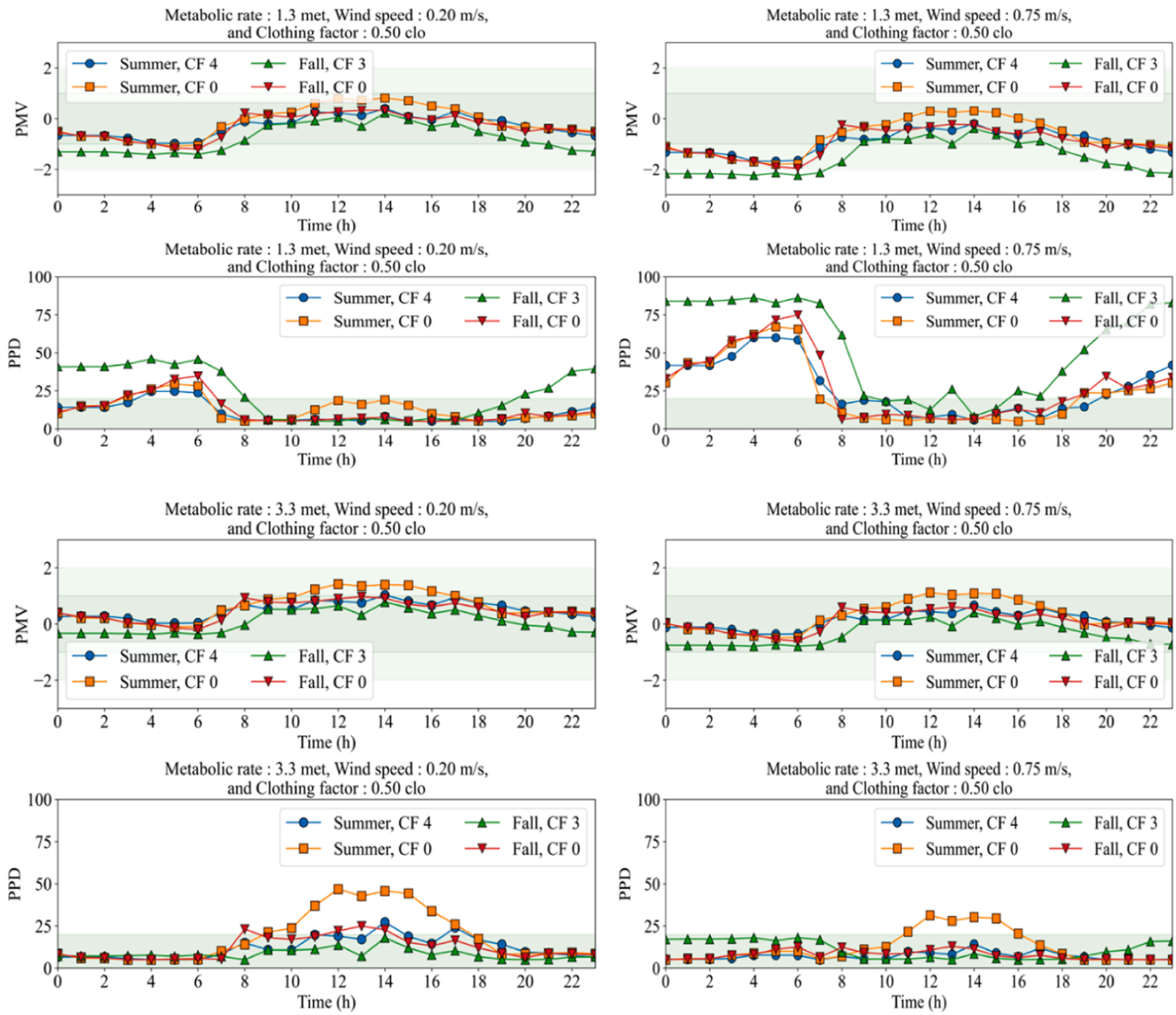


Fig. 12. PMV and PPD values of PCGH under summer and fall with different factors (cloud cover, metabolic rate, clothing factor, and airspeed).

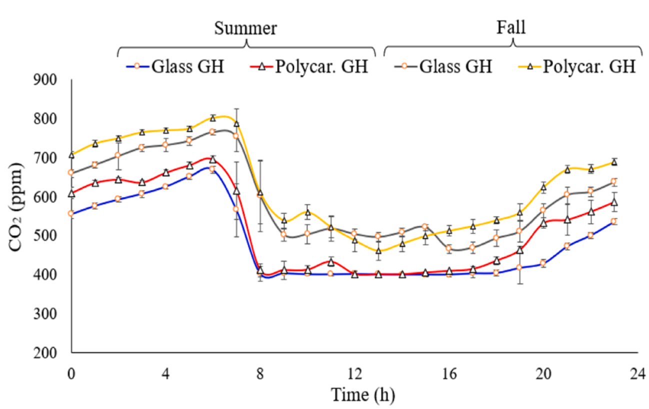


Fig. 13. CO_2 concentration variation of the glass and polycarbonate GHs.

exposure levels. Supplying workers with appropriate PPE, such as wide-brimmed hats, long-sleeved shirts, and UV-protective sunglasses, is also recommended. The workers are encouraged to use sunscreen with a high sun protection factor (SPF) to shield exposed skin from UV radiation. While optimizing greenhouse covers for energy efficiency, it is crucial to consider UV thresholds as a limiting constraint. This will help strike a balance between energy efficiency goals and the provision of adequate UV protection for worker safety. The combination of protective measures like changing the work schedule to avoid the most uncomfortable situations, easy access to water, way to cool off or warm up as required, training to reduce health risks, and continuous supervision of the worker's physical condition are needed.

- ➢ Compared with the working environment of other industries, each factor related to the greenhouse workers' health and safety needs to be assessed more precisely. A detailed questionnaire can be prepared to evaluate thermal comfort and validate the calculated PMV values for greenhouse applications. Also, more studies are recommended to assess the health and safety-related parameters based on standard practices and the indoor environment in greenhouses. Most studies used the metabolic rate and clothing factors from ASHRAE fundamental and other sources, which might need to be investigated for greenhouse working conditions.
- ➢ Natural and forced ventilated greenhouses without supplemental CO_2 supply never exceed the conservative safety thresholds recommended by ASHRAE, but the scenario can be different in greenhouses with CO_2 supplementation, and future studies should investigate such a scenario.

Finally, it is worth mentioning that the greenhouse environment is optimized for growing plants, not for human beings. However, as the workers stay a long time inside the greenhouse, it's critical to have some protective and preventive measures based on the research-based assessment of health safety, heat stress, and comfort inside the greenhouses.

Ethical statement for solid state Ionics

Hereby, I /insert author name/ consciously assure that for the manuscript /insert title/ the following is fulfilled:

(1) This material is the authors' own original work, which has not been previously published elsewhere.
(2) The paper is not currently being considered for publication elsewhere.
(3) The paper reflects the authors' own research and analysis in a truthful and complete manner.
(4) The paper properly credits the meaningful contributions of co-authors and co-researchers.
(5) The results are appropriately placed in the context of prior and existing research.
(6) All sources used are properly disclosed (correct citation). Literally copying of text must be indicated as such by using quotation marks and giving proper reference.
(7) All authors have been personally and actively involved in substantial work leading to the paper, and will take public responsibility for its content.
(8) No animals or human used as subject for this study

The violation of the Ethical Statement rules may result in severe consequences.

I agree with the above statements and declare that this submission follows the policies of Solid State Ionics as outlined in the Guide for Authors and in the Ethical Statement.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgement

This project was supported by the Centers for Disease Control and Prevention, National Institute for Occupational Safety and Health (CDCNIOSH) Cooperative Agreement # U54 OH007550. We would like to sincerely acknowledge Mars Wrigley for allowing us to experiment in their greenhouse and providing logistics support for the experiment.

References

[1] FAO, The future of food and agriculture, Food Agricult. Organiz. United Nat. (2017) 1–52.
[2] P.P. Reddy, Sustainable Crop Protection Under Protected Cultivation, Springer Singapore, Singapore, 2016, https://doi.org/10.1007/978-981-287-952-3.
[3] R.R. Shamshiri, et al., Advances in greenhouse automation and controlled environment agriculture: a transition to plant factories and urban agriculture, Int. J. Agricul. Biol. Eng. 11 (1) (2018), https://doi.org/10.25165/j.ijabe.20181101.3210.
[4] N. Gruda, M. Bisbis, J. Tanny, Impacts of protected vegetable cultivation on climate change and adaptation strategies for cleaner production – a review, J. Clean Prod. 225 (2019) 324–339, https://doi.org/10.1016/j.jclepro.2019.03.295.
[5] M. Iqbal, An Introduction to Solar Radiation, Academic Press, Toronto, Canada, 1983.
[6] M.C. Vázquez-Hernández, I. Parola-Contreras, L.M. Montoya-Gómez, I. Torres-Pacheco, D. Schwarz, R.G. Guevara-González, Eustressors: chemical and physical stress factors used to enhance vegetables production, Sci. Hortic. 250 (2019) 223–229, https://doi.org/10.1016/j.scienta.2019.02.053.
[7] A. Semenov, G. Kozhushko, T. Sakhno, Influence of UV radiation in pre-sowing treatment of seeds of crops, Technol. Audit Prod. Res. 1 (3) (2019) 30–32, https://doi.org/10.15587/2312-8372.2019.159954, 45.
[8] S. Neugart, et al., The effect of temperature and radiation on flavonol aglycones and flavonol glycosides of kale (Brassica oleracea var. sabellica, Food Chem. 133 (4) (2012) 1456–1465, https://doi.org/10.1016/j.foodchem.2012.02.034.
[9] S.K. Amar, S. Goyal, A.K. Srivastav, D. Chopra, R.S. Ray, Combined effect of Benzophenone-2 and ultraviolet radiation promote photogenotoxicity and photocytotoxicity in human keratinocytes, Regul. Toxicol. Pharmacol. 95 (2018) 298–306, https://doi.org/10.1016/J.YRTPH.2018.04.003.
[10] M.A. Serrano, J.C. Moreno, Spectral transmission of solar radiation by plastic and glass materials, J. Photochem. Photobiol. B 208 (2020), 111894, https://doi.org/10.1016/J.JPHOTOBIOL.2020.111894.
[11] D.G. Quintero-Arias, J.F. Acuña-Caita, C. Asensio, J.L. Valenzuela, Ultraviolet transparency of plastic films determines the quality of lettuce (Lactuca sativa L.) Grown in a greenhouse, Agronomy 11 (2) (2021) 358, https://doi.org/10.3390/agronomy11020358.
[12] J. D'Orazio, S. Jarrett, A. Amaro-Ortiz, T. Scott, UV radiation and the skin, Int. J. Mol. Sci. 14 (6) (2013) 12222–12248, https://doi.org/10.3390/IJMS140612222.
[13] B.M. Stepanski, J.A. Mayer, Solar protection behaviors among outdoor workers, J. Occup. Environ Med. 40 (1) (1998).
[14] M.F.C. Ruales, et al., UVR exposure and prevention of street construction workers in Colombia and Germany, Int. J. Environ. Res. Public Health 19 (12) (2022), https://doi.org/10.3390/ijerph19127259.
[15] S.Y. Ing, F.D. Ashbury, L.D. Marrett, L. From, K.V. Perry, Use of focus group methodology in the development of an Ontario farmers' sun safety survey, Chronic Dis. Can. 23 (2) (2002) 65–70.
[16] M.B. Schenker, M.R. Orenstein, S.J. Samuels, Use of protective equipment among California farmers, Am. J. Ind. Med. 42 (5) (2002) 455–464, https://doi.org/10.1002/ajim.10134.
[17] M. Moehrle, B. Dennenmoser, C. Garbe, Continuous long-term monitoring of UV radiation in professional mountain guides reveals extremely high exposure, Int. J. Cancer 103 (6) (2003) 775–778, https://doi.org/10.1002/ijc.10884.
[18] R.A. García-Ruiz, J. López-Martínez, J.L. Blanco-Claraco, J. Pérez-Alonso, Á. J. Callejón-Ferre, Ultraviolet Index (UVI) inside an Almería-type greenhouse (Southeastern Spain), Agronomy 10 (1) (2020) 1–17, https://doi.org/10.3390/agronomy10010145.
[19] B.W. Jones, Capabilities and limitations of thermal models for use in thermal comfort standards, Energy Build 34 (6) (2002) 653–659, https://doi.org/10.1016/S0378-7788(02)00016-6.
[20] Centers for Disease Control and Prevention-USA, Heat-related deaths among crop workers—United States, 1992-2006, JAMA 300 (9) (2008) 1017, https://doi.org/10.1001/jama.300.9.1017.
[21] A.J. Callejón-Ferre, J. Pérez-Alonso, A. Carreño-Ortega, B. Velázquez-Martí, Indices of ergonomic-psycholsociological workplace quality in the greenhouses of Almería (Spain): crops of cucumbers, peppers, aubergines and melons, Saf. Sci. 49 (5) (2011) 746–750, https://doi.org/10.1016/j.ssci.2010.12.009.
[22] L. Okushima, S. Sase, I.B. Lee, B.J. Bailey, Thermal environment and stress of workers in Naturalley ventilated greenhouses under mild climates, in: Proceedings of the Fifth International Symposium on Protected Cultivation in Mild Winter Climates, 2001, pp. 793–798.
[23] A.M. Abdel-Ghany, I.M. Al-Helal, M.R. Shady, Effect of the evaporative cooling on the human thermal comfort and heat stress in a greenhouse under arid conditions, Adv. Meteorol. (2013), https://doi.org/10.1155/2013/361471.
[24] T. Shimazu, H. Hamamoto, T. Okada, T. Ikfda, K. Tanaka, Microclimate and human thermal comfbrt in pipe greenhouses with insect-proof screens for vegetable cultivation with restricted use of chemical pesticides, Agricul. Meteorol. 60 (5) (2005) 813–816.
[25] A.J. Callejon-Ferre, F. Manzano-Agugliaro, M. Diaz-Perez, J. Carreno-Sanchez, Improving the climate safety of workers in Almería-type greenhouses in Spain by predicting the periods when they are most likely to suffer thermal stress, Appl. Ergon. 42 (2) (2011) 391–396, https://doi.org/10.1016/j.apergo.2010.08.014.
[26] A. Marucci, B. Pagniello, D. Monarca, M. Cecchini, A. Colantoni, P. Biondi, Heat stress suffered by workers employed in vegetable grafting in greenhouses, J. Food Agric. Environ. 10 (2) (2012) 1117–1121.
[27] H.P.A. Illing, Is working in greenhouses healthy? Evidence concerning the toxic risks that might affect greenhouse workers, Occup. Med. (Chic Ill) 47 (5) (1997) 281–293, https://doi.org/10.1093/OCCMED/47.5.281.
[28] J. Jurewicz, D. Kouimintzis, A. Burdorf, W. Hanke, C. Chatzis, A. Linos, Occupational risk factors for work-related disorders in greenhouse workers, J. Publ. Health 15 (4) (2007) 265–277, https://doi.org/10.1007/S10389-007-0129-X/TABLES/5 (Bangkok).
[29] Grand View Research, "Greenhouse market size, share & trends analysis report by type (Glass Greenhouse, Plastic Greenhouse), By Offering (Hardware, Software, Services), By Crop Type, By End-user, By Region, And Segment Forecasts, 2023–2030," 2022. https://www.grandviewresearch.com/industry-analysis/greenhouse-market-report.
[30] USDA-NASS, "USDA - national agricultural statistics service - Charts and Maps - 2014 crop progress and conditions." 2014. [Online]. Available: https://www.nass.usda.gov/Charts_and_Maps/Crop_Progress_&_Condition/2014/index.php.
[31] U.S. BLS, "National occupational employment and wage estimates," May 2022. https://www.bls.gov/oes/current/oes452092.htm#nat (accessed Jul. 05, 2023).
[32] J.B. Kerr, et al., The Canadian ozone watch and UV-B advisory programs, NASA. Goddard Space Flight Center Ozone Troposph. Stratosph. (Part 2) (1994).

[33] WHO and ICNIRP, "Global solar UV index: a practical guide," 2002.
[34] A. Price, An apparatus for personalized atmospheric and flight data collection aboard high altitude weather balloons, HardwareX 6 (2019) e00077, https://doi.org/10.1016/J.OHX.2019.E00077.
[35] Z.Y. Su, Y.N. Lin, V.R.L. Shen, Intelligent environmental monitoring system based on LoRa long range technology, in: Proceedings of the IEEE Eurasia Conference on IOT, Communication and Engineering, ECICE 2019, 2019, pp. 354–357, https://doi.org/10.1109/ECICE47484.2019.8942778.
[36] M.B. Rhudy, N. Greenauer, C. Mello, Wearable light data logger for studying physiological and psychological effects of light data, HardwareX 8 (2020) e00157, https://doi.org/10.1016/J.OHX.2020.E00157.
[37] D. Sales-Lérida, J. Grosso, P.M. Martínez-Jiménez, M. Manzano, A low cost and eco-sustainable device to determine the end of the disinfection process in SODIS, Sensors 23 (2) (2023) 1–18, https://doi.org/10.3390/s23020575.
[38] ISO 7243, "Hot Environments e Estimation of the Heat Stress onWorking Man, Based on the WBGT-index (Wet Bulb Globe Temperature)," Geneva, Switzerland., 1989.
[39] ANSI/ASHRAE Standard 55, Thermal environmental conditions for human occupancy, ASHRAE Stand. (55) (2013).
[40] R. Hajizadeh, S. Farhang Dehghan, F. Golbabaei, S.M. Jafari, M. Karajizadeh, Offering a model for estimating black globe temperature according to meteorological measurements, Meteorol. Appl. 24 (2) (2017) 303–307, https://doi.org/10.1002/met.1631.
[41] T.E. Bernard, M. Pourmoghani, Prediction of workplace wet bulb global temperature, Appl. Occup. Environ Hyg. 14 (2) (1999) 126–134, https://doi.org/10.1080/104732299303296.
[42] ASHRAE, ASHRAE Handbook of Fundamentals, SI Edition, American Society of Heating Ventilation Refrigeration and Air-conditioning Engineers, Atlanta, USA, 2017.
[43] W. Ji, et al., Interpretation of standard effective temperature (SET) and explorations on its modification and development, Build Environ. 210 (2022), 108714, https://doi.org/10.1016/j.buildenv.2021.108714.
[44] J. Vatani, F. Golbabaei, S.F. Dehghan, A. Yousefi, Applicability of universal thermal climate index (UTCI) in occupational heat stress assessment: a case study in brick industries, Ind. Health 54 (1) (2016) 14–19, https://doi.org/10.2486/indhealth.2015-0069.
[45] S. Zare, N. Hasheminejad, H.E. Shirvan, R. Hemmatjo, K. Sarebanzadeh, S. Ahmadi, Comparing Universal Thermal Climate Index (UTCI) with selected thermal indices/environmental parameters during 12 months of the year, Weather Clim. Extrem. 19 (2017) 49–57, https://doi.org/10.1016/j.wace.2018.01.004. December 2018.
[46] F. Tartarini, S. Schiavon, Pythermalcomfort: a Python package for thermal comfort research, SoftwareX 12 (2020), 100578, https://doi.org/10.1016/j.softx.2020.100578.
[47] ICC, "International Building Code (IBC). 2018a.," 2018. https://codes.iccsafe.org/s/IBC2018/chapter-3-occupancy-classification-and-use/IBC2018-Ch03-Sec312.1.1 (accessed Jul. 05, 2023).
[48] ICC, "International Building Code (IBC). 2018b.," 2018. https://codes.iccsafe.org/content/IBC2018, Chapter-10-means-of-egress#:~:text=1004.8Concentrated20business20use20areas; Where20approved20by20the20buildingof20 gross20occupiable20floor20space (accessed Jul. 05, 2023).
[49] J. Babiak, B.W. Olesen, and D. Petras, "REHVA Guidebook No 7: low temperature heating and high temperature cooling.," Brussels., 2009.
[50] J. Woolley, S. Schiavon, F. Bauman, P. Raftery, J. Pantelic, Side-by-side laboratory comparison of space heat extraction rates and thermal energy use for radiant and all-air systems, Energy Build 176 (2018) 139–150, https://doi.org/10.1016/j.enbuild.2018.06.018.
[51] E. Teitelbaum, et al., Globe thermometer free convection error potentials, Sci. Rep. 10 (1) (2020) 1–13, https://doi.org/10.1038/s41598-020-59441-1.
[52] M. Dawe, P. Raftery, J. Woolley, S. Schiavon, F. Bauman, Comparison of mean radiant and air temperatures in mechanically-conditioned commercial buildings from over 200,000 field and laboratory measurements, Energy Build 206 (2020), 109582, https://doi.org/10.1016/j.enbuild.2019.109582.
[53] A. Pakari, S. Ghani, Airflow assessment in a naturally ventilated greenhouse equipped with wind towers: numerical simulation and wind tunnel experiments, Energy Build 199 (2019) 1–11, https://doi.org/10.1016/J.ENBUILD.2019.06.033.
[54] B.E. Ainsworth, et al., 2011 Compendium of Physical Activities: a second update of codes and MET values, Med. Sci. Sports Exerc. 43 (8) (2011) 1575–1581, https://doi.org/10.1249/MSS.0b013e31821ece12.
[55] Cardinal Glass Industries, "Custom Tempered Glass," Oct. 2022. https://www.cardinalcorp.com/products/tempered-glass/custom-tempered-glass/.
[56] Duralight Plastics, "Clear 6mm Twin Wall VEROLITETM polycarbonate panel,". https://www.duralightplastics.com/6mm-twin-wall-verolite-clear.html.
[57] Svensson, "TEMPA 5557 D,". https://www.ludvigsvensson.com/en/climate-screens/climate-screens-products/tempa/tempa-5557-d/.
[58] A. Rodriguez-Martinez, et al., Height and body-mass index trajectories of school-aged children and adolescents from 1985 to 2019 in 200 countries and territories: a pooled analysis of 2181 population-based studies with 65 million participants, Lancet 396 (10261) (2020) 1511–1524.
[59] M.A.P. Pertijs, A.L. Aita, K.A.A. Makinwa, J.H. Huijsing, Low-cost calibration techniques for smart temperature sensors, IEEE Sens. J. 10 (6) (2010) 1098–1105, https://doi.org/10.1109/JSEN.2010.2040730.
[60] L. Greenspan, Humidity fixed points of binary saturated aqueous solutions, J. Res. Natl. Bur. Stand A Phys. Chem. 81A (1) (1977) 89–96, https://doi.org/10.6028/jres.081A.011.
[61] S. Jafariserajehlou, L. Mei, M. Vountas, V. Rozanov, J.P. Burrows, R. Hollmann, A cloud identification algorithm over the Arctic for use with AATSR-SLSTR measurements, Atmos. Meas. Tech. 12 (2) (2019) 1059–1076, https://doi.org/10.5194/AMT-12-1059-2019.
[62] M.S. Ahamed, H. Guo, and K. Tanino, "Cloud cover-based models for estimation of global solar radiation: a review and case study," *10.1080/15435075.2021.1941043*, vol. 19, no. 2, pp. 175–189, 2021, doi:10.1080/15435075.2021.1941043.
[63] L. Luo, D. Hamilton, B. Han, Estimation of total cloud cover from solar radiation observations at Lake Rotorua, New Zealand, Solar Energy 84 (3) (2010) 501–506, https://doi.org/10.1016/J.SOLENER.2010.01.012.
[64] M.S. Ahamed, R. Zmeureanu, N. Cortrufo, and J. Candanedo, "Gray-box virtual sensor of the supply air temperature of air handling units," vol. 26, no. 8, pp. 1151–1162, Sep. 2020, doi:10.1080/23744731.2020.1785812.
[65] ASHRAE, "Guideline 2-2010 - engineering analysis of experimental data," Atlanta, USA, 2010.
[66] P. Gies, C. Roy, J. Javorniczky, S. Henderson, L. Lemus-Deschamps, C. Driscoll, Global Solar UV index: Australian measurements, forecasts and comparison with the UK, Photochem. Photobiol. 79 (1) (2004) 32, https://doi.org/10.1562/0031-8655(2004)79<32:gsuiam>2.0.co;2.
[67] A. Rafiq, W.H. Na, A. Rasheed, J.W. Lee, H.T. Kim, H.W. Lee, Measurement of Longwave radiative properties of energy-saving greenhouse screens, J. Agricult. Eng. 52 (3) (2021), https://doi.org/10.4081/JAE.2021.1209.
[68] G.M. Budd, Wet-bulb globe temperature (WBGT)—Its history and its limitations, J. Sci. Med. Sport 11 (1) (2008) 20–32, https://doi.org/10.1016/j.jsams.2007.07.003.
[69] S. Conti, et al., General and specific mortality among the elderly during the 2003 heat wave in Genoa (Italy), Environ Res 103 (2) (2007) 267–274, https://doi.org/10.1016/j.envres.2006.06.003.
[70] F.R. d'Ambrosio Alfano, B.I. Palella, G. Riccio, Notes on the Calculation of the PMV Index by Means of Apps, Energy Procedia 101 (2016) 249–256, https://doi.org/10.1016/j.egypro.2016.11.032.
[71] W.A. Andreasi, R. Lamberts, C. Cândido, Thermal acceptability assessment in buildings located in hot and humid regions in Brazil, Build Environ 45 (5) (2010) 1225–1232, https://doi.org/10.1016/j.buildenv.2009.11.005.
[72] P. Ole Fanger, J. Toftum, Extension of the PMV model to non-air-conditioned buildings in warm climates, Energy Build 34 (6) (2002) 533–536, https://doi.org/10.1016/S0378-7788(02)00003-8.
[73] K. Pallavi, J.D. Mallapur, K.Y. Bendigeri, Remote sensing and controlling of greenhouse agriculture parameters based on IoT, in: Proceedings of the International Conference on Big Data, IoT and Data Science, BID 2017 2018-Janua, 2018, pp. 44–48, https://doi.org/10.1109/BID.2017.8336571.
[74] D.A. Way, J.R. Stinziano, H. Berghoff, R. Oren, How well do growing season dynamics of photosynthetic capacity correlate with leaf biochemistry and climate fluctuations? Tree Physiol. 37 (7) (2017) 879–888, https://doi.org/10.1093/TREEPHYS/TPX086.
[75] J.L. Osuna, D.D. Baldocchi, H. Kobayashi, T.E. Dawson, Seasonal trends in photosynthesis and electron transport during the Mediterranean summer drought in leaves of deciduous oaks, Tree Physiol. 35 (5) (2015) 485–500, https://doi.org/10.1093/TREEPHYS/TPV023.
[76] J.A. Leech, W.C. Nelson, R.T. Burnett, S. Aaron, M.E. Raizenne, It's about time: a comparison of Canadian and American time–activity patterns, J. Expo. Sci. Environ. Epidemiol. 12 (6) (2002) 427–432, https://doi.org/10.1038/sj.jea.7500244.
[77] P.S. Hui, L.T. Wong, and K.W. Mui, "Feasibility study of an express assessment protocol for the indoor air quality of air-conditioned offices," vol. 15, no. 4, pp. 373–378, Jul. 2016, doi:10.1177/1420326X06067866.
[78] N. Mahyuddin and H.B. Awbi, "A review of CO2 measurement procedures in ventilation research," vol. 10, no. 4, pp. 353–370, 2016, doi:10.1080/14733315.2012.11683961.
[79] C. Papachristou, K. Foteinaki, O.B. Kazanci, B.W. Olesen, Structures that include a semi-outdoor space: part 2: thermal environment, in: CLIMA 2016 - Proceedings of the 12th REHVA World Congress (Vol. 10), 2016, pp. 343–354.
[80] A. Simone, B.W. Olesen, J.L. Stoops, and A.W. Watkins, "Thermal comfort in commercial kitchens (RP-1469): procedure and physical measurements (Part 1)," vol. 19, no. 8, pp. 1001–1015, Nov. 2013, doi:10.1080/10789669.2013.840494.
[81] R.L. Yang, L. Liu, Y. De Zhou, Predicted thermal sensation index for the hot environment in the spinning workshop, Math. Probl. Eng. (2015), https://doi.org/10.1155/2015/980619.