PAR (Photosynthetically Active Radiation) Performances in Greenhouses: A Climate-based Investigation across China

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Abstract

Photosynthetically Active Radiation (PAR) is critically required for sustaining plant and vegetable growth. This study investigated PAR performances in two typical large-scale greenhouses using an advanced method of climate-based solar modelling in China. Seven Chinese locations were studied in terms of daylight climate zones and latitudes. The solar simulation was conducted via RADIANCE (ray-tracing solar and light simulation package). Key findings are: 1) This study indicates that a climate-based analysis (using daylight climate zones) has be proved as more useful and practical than the methods based on clear sky and solar geometries. 2) In general, the annual PAR availability receives higher impacts of climate than the latitude, while the latitude can clearly affect the PAR peak time. 3) Given the PAR availability, the A-frame greenhouse combined with the longitudinal orientation of east-west has been proved as an optimal design strategy at most locations in China; however, if the longitudinal orientation of north-south will have to be applied, the Barrel-vault greenhouse can bring in a higher PAR level. These design strategies could be considered when planning a passive solution for the greenhouses in China or regions with similar climates.

Keywords: Photosynthetically Active Radiation (PAR), Greenhouse, RADIANCE simulation, Daylight climate zone, China

1. Introduction

Photosynthetically Active Radiation (PAR) has been regarded as one of the most important environmental factors when planning structures and configurations of greenhouses (Impron et al., 2007). It has a spectral range of solar radiation from 400 to 700 nm that photosynthetic organisms are able to use in the process of photosynthesis (Hall, 1999). Having a similar wavelength as visual light, PAR varies in season, the time of day and latitude, and is critically required for sustaining plant and vegetable growth (McCree, 1977). In China, passive solutions of solar energy utilization have been broadly applied in simple and small-scale greenhouses (Tong et al., 2013). With a fast-growth of indoor farming industry since 1990s, many active energy/environmental strategies (e.g. PV, heat pumps) have been studied and adopted to improve the constructions of traditional greenhouse in some Chinese areas (Wang et al., 2017). More recently, due to the increasing requirement of low carbon design in agricultural facilities (Cuce et al., 2016), it seems that the passive solar solutions for greenhouses have returned to be a research trend in the area of indoor farming.

Given the passive solar design in buildings or similar facilities, the shape of roof with a large glazing area was recognized as one critical factor affecting solar radiation transmissivity (including transmission of daylight, PAR, etc.) (Sharples & Lash, 2007). In an early study (Navvab & Selkowitz, 1984), fourteen roof structures were examined under different sky conditions and some key findings were therefore produced as follows: 1) Most monitor roof systems were found to have a similar property of transmittance (direct light), which is more sensitive to solar altitude than the pyramids, vaults and A-frames. 2) The A-frame roofs, however, have a higher transmittance for diffuse skylight (overcast sky) than the monitor systems. A later Canadian study (Laouadi & Atif, 2001) found that the dome is the best shape for admitting sunbeam in winter (low altitude). A numerical model of radiative PAR transfer was developed to evaluate its distributions in a Barrel-vault glazed greenhouse (Farkas et al., 2001). Similarly, it has been found that in winter the barrel-vault roofs were more effective on the beam light transmitting than flat skylights with similar glazing attributes (Laouadi, 2005). In addition, one recent investigation was conducted to test different elliptic curved surface aspect ratios to reach the optimum design of barrel-vault greenhouse, on the basis of climates of North Africa and the solar radiation received at the floor (El-

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Maghlany et al., 2015). In general, A-frame and Barrel-vault have been accepted as two typical roof types in greenhouses according to the solar gain (Sethi, 2009; Tong et al., 2013).

Apparently, in greenhouses, the orientation is another important environmental factor in terms of the amount of solar gains (including PAR) and relevant energy demand (heating and cooling) across various seasons (Gupta and Chandra, 2002; Stanciu et al., 2016). The combined effects of orientation and latitude can significantly take effect on the direct solar radiation transmissivity (Kurata, 1993). One Indian study also investigated the combined effect of shapes and orientations in one greenhouse on the energy demand and solar radiation availability, using a proposed thermal model (Sethi 2009). East-west was proved as the best orientation at one subtropical location (31°N) and suitable for annual greenhouse operation, since this orientation can bring in higher global radiation in winter and lower solar gain in summer. Similar findings have been achieved in one Iranian study of an east-west oriented single span greenhouse with north brick wall (Mobtaker et al., 2016), as well as one fundamental study of greenhouse configurations in Turkey with a focus on the solar energy utilization (Kendirli, 2006). However, these studies were conducted at the locations dominated by the clear sky. For locations with mixed sky conditions (overcast, intermediate and clear sky), a climate-based analysis would be required.

In this article, a simulation study of two typical greenhouses were presented based on five daylight climate zones and seven locations in China. RADIANCE (RADIANCE, 2018), an advanced ray-tracing package, was applied to simulate the availability of solar irradiance and PAR in these greenhouses. A comprehensive climate-based analysis was thus achieved to help plan and construct greenhouses across typical regions in this country.

2. Methods and materials

2.1. Daylight climate zones and locations

According to the building regulation (Ministry of Housing and Urban-Rural Development, 2013), five daylight climate zones are currently used to indicate the daylight / solar availability in the built environment in China. They were developed using the annual profile of solar irradiation monitored by 14 land-based weather stations across this country. As shown in Table 1, the ranges of annual-averaged unobstructed illuminance (Eq) can be found for each zone. Severn Chinese locations have been studied as: Lhasa (zone I; 29.7° N, 91.1° E); Yinchuan (zone II; 38.5° N, 106.2° E); Beijing (zone III; 39.9° N, 116.4° E), Guangzhou (zone IV; 23.1° N, 113.3° E), Wuhan (zone IV; 30.6° N, 114.3° E), Changchun (zone IV; 43.8° N, 125.3° E); Chengdu (zone V; 30.6° N, 104.1° E). These locations are representatives of big cities across the country. In addition, they were selected based on an aim to cover most of the important agricultural regions and big urban-rural areas. The local weather data of these locations were used to support the solar simulations (section 2.3).

Tab. 1: Daylight climate zones, annual-averaged illuminance (Eq), and locations in China

Zone Number	**I**	**II**	**III**	**IV**	**V**
Ranges of annual-averaged unobstructed illuminance, Eq (klx)	≥28	[26 28)	[24 26)	[22 24)	<22
Locations studied	Lhasa	Yinchuan	Beijing	Guangzhou, Wuhan, Changchun	Chengdu

2.2. Greenhouse models

As displayed in Figure1, the greenhouse model has a rectangular plan (length × width: 15×40 m; area: 600 m^2), and two section types varying in roof: A-frame (Sharples & Lash, 2007) & Barrel-vault (Laouadi, 2005). The sections show that the greenhouse has a multi-span structure and the width of single span is 3 m. Each section has two spatial parts of roof space (height: 1.5 m) and normal space (height: 4.2 m). Two orientations were studied including: the greenhouse length was aligned to east-west or north-south. Therefore, in total, there are four cases studied, such as A-frame & east-west, A-frame & north-south, Barrel-vault & east-west, and Barrel-vault & north-south.

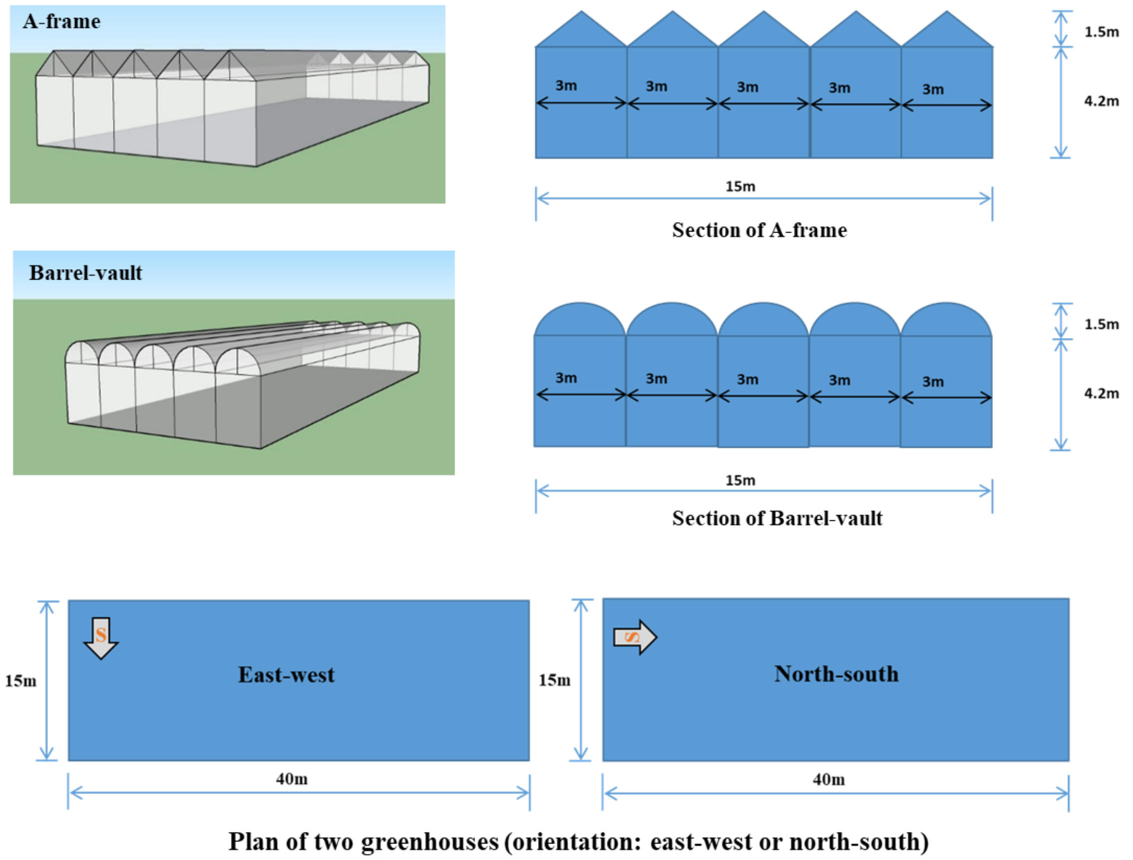

Fig. 1: Configures, dimensions and orientations of two typical greenhouses studied

2.3. PAR calculation and simulation

In the field of plant science, PAR can be expressed by photosynthesis photosynthetic photon flux (μmol/m²s) or solar irradiance (W/m²) (Sun et al., 2017). The theoretical relationship between the aforementioned two variables can be defined by the equation:

$$PAR(\lambda) = \frac{F_\lambda \lambda}{N_A hc} \qquad \text{(eq. 1)}$$

where PAR(λ) is the photon flux, F_λ is the solar irradiance, λ is the wavelength, N_A is the Avogadro Number, h is the Planck constant, and c is the speed of light. In addition, there is an experimental method to get PAR through measuring global solar irradiance in an outdoor environment. In this study, PAR values were then achieved using an empirical equation (Dong et al., 2011; Zhou et al., 2017):

$$PAR = \eta_0 Q \quad \text{(eq. 2)}$$

where Q is global solar irradiance, W/m²; η0 is the factor related to the location [on average, η0=0.44 according to 7 Chinese locations studied in this reference (Zhou et al., 2017)]. Thus, PAR was displayed using solar irradiance (W/m²) in this study.

Developed for ray-tracing lighting/daylighting (irradiance) simulation, RADIANCE (RADIANCE, 2018) can be used as a tool to calculate the global solar irradiance (W/m²) at a specific position and under various sky conditions (e.g. overcast, intermediate and clear sky). This study adopted RADIANCE to calculate the global solar irradiance across the floor of the four greenhouse models mentioned above.

3. Results

This section includes PAR performances in two greenhouses with two orientations and seven locations, and a comparison of PAR between the two orientations.

3.1. Orientation: east-west

Figure 2-4 give variations of the monthly-averaged PAR on the floor of two greenhouses at seven locations, with a longitudinal orientation of east-west.

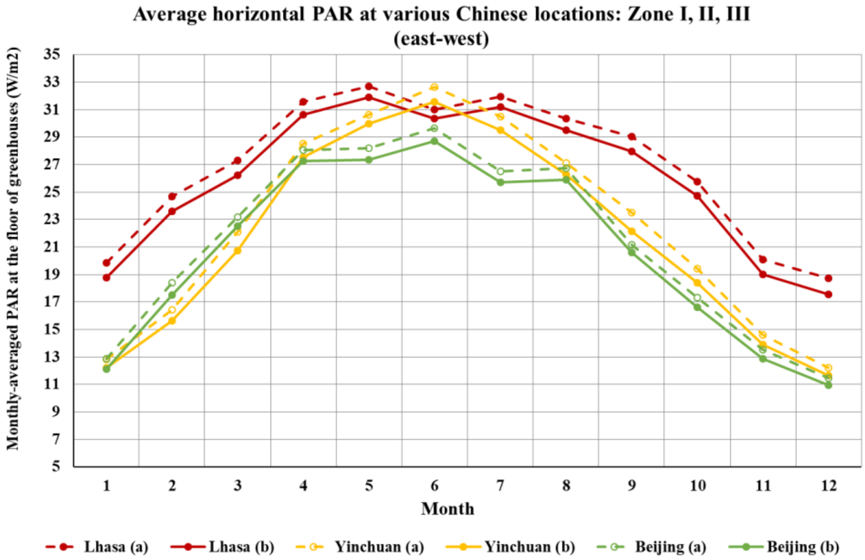

Fig. 2: Monthly-averaged PAR at the floor of two greenhouses (zone I, II and III).

Figure 2 shows PAR variations at Lhasa (zone I), Yinchuan (zone II), and Beijing (zone III), all of which receive the highest levels of solar irradiance in China. Generally, A-frame greenhouses have higher PAR than Barrel-vault models across 12 months. Taking the Barrel-vault model as a reference, percentage differences of monthly PAR in A-frame model have the ranges of 2.14~6.56% (Lhasa), 2.82~6.26% (Beijing), and 2.31~6.12% (Yinchuan). The differences in winter are larger than those in summer. As for the three locations, Lhasa generally sees the higher PAR than Yinchuan and Beijing, while Yinchuan receives higher PAR than Beijing from April to August and similar PAR levels as Beijing in other periods. PAR peaks at the period from May to July at all locations.

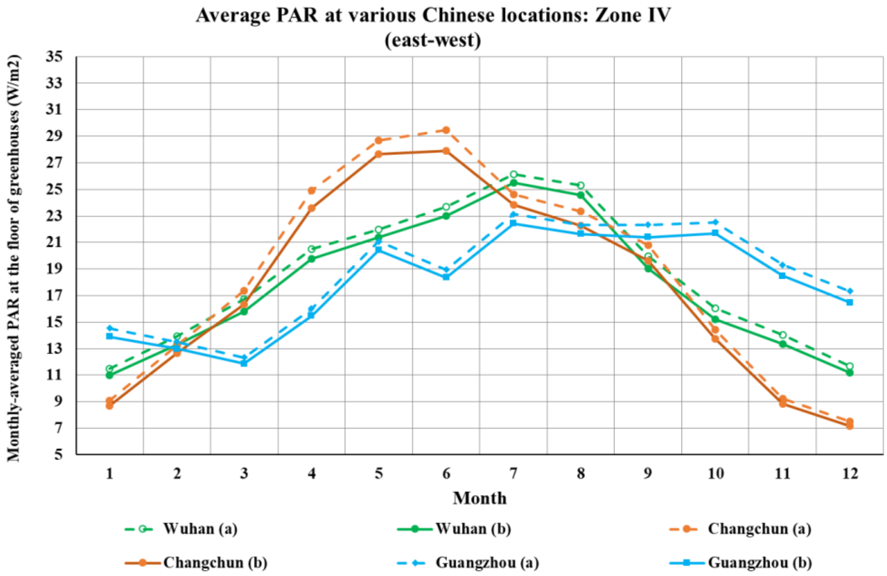

Fig. 3: Monthly-averaged PAR at the floor of two greenhouses (zone IV).

According to the regulation (Ministry of Housing and Urban-Rural Development, 2013), there are many important big cities located in the daylight climate zone IV. Therefore, three locations (Changchun, Wuhan and Guangzhou) were assessed to represent three Chinese regions with high (north), middle and low (south) latitudes respectively (Figure 3). Clearly, the latitude takes impact on the peak period of PAR. Changchun, Wuhan and Guangzhou see

PAR peak during the periods of (May to June), (July to August), and (July to October) respectively. Similar to Figure 2, Barrel-vault greenhouses will deliver relatively lower PAR than A-frame models, with the percentage difference ranges of 3.29~6.34% (Changchun), 2.48~5.69% (Wuhan), 3.13~5.19% (Guangzhou). The differences of PAR between two greenhouses tend to be lower with the decreasing latitude.

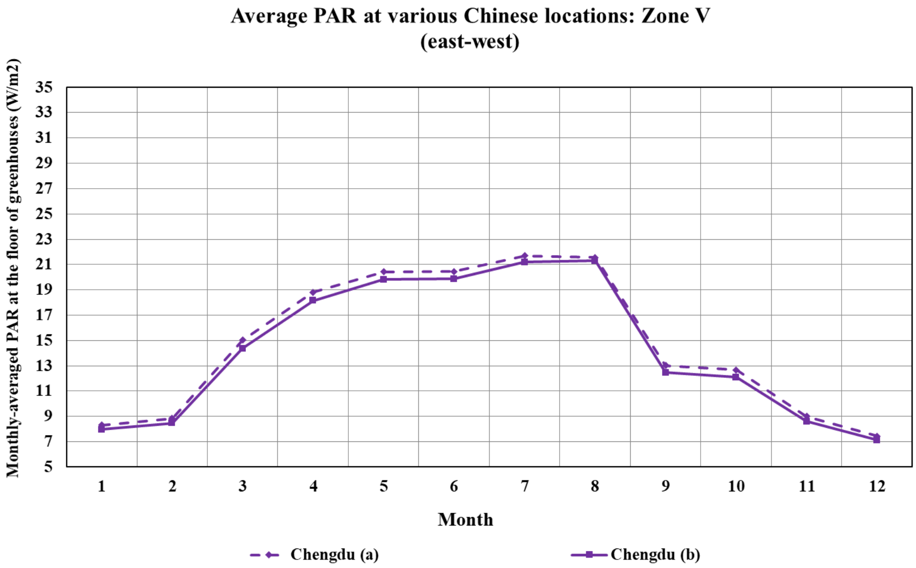

Fig. 4: Monthly-averaged PAR at the floor of two greenhouses (zone V).

Figure 4 displays PAR variations in Chengdu, where the lowest solar irradiance level is typically found (zone V). PAR has a very low level at the beginning of the year (January and February), and starts to go up from early spring (March) to summer. It peaks at July and August, and dramatically drops in autumn and winter. A-frame greenhouses can also bring in relatively higher PAR than Barrel-vault models (percentage difference range: 1.28-4.76%).

Tab. 2: Annual-averaged PAR in the two greenhouses (east-west)

Annual-averaged PAR (W/m^2)							
Locations	**Lhasa**	**Yinchuan**	**Beijing**	**Guangzhou**	**Wuhan**	**Changchun**	**Chengdu**
A-frame	26.92	22.55	21.42	18.61	18.45	18.56	14.77
Barrel-vault	25.96	21.63	20.67	17.92	17.75	17.69	14.28

Given the annual-averaged PAR (Table 2), it is normal that Lhasa and Chengdu have the maximum and minimum values respectively; while the latitude does not take clear effect on this value at three locations of zone IV, including Changchun, Wuhan and Guangzhou. Yinchuan just has a slightly higher PAR than Beijing. Similarly, A-frame roof could lead to slightly higher PAR than Barrel-vault roof at all locations.

3.2. Orientation: north-south

As regards the orientation of north-south, Figure 5-7 present variations of the monthly-averaged PAR on the floor of two greenhouses at seven locations.

Compared with Figure 4 (east-west), Figure 5 (north-south) shows some differences of PAR variations at Lhasa (zone I), Yinchuan (zone II), and Beijing (zone III). For this orientation, A-frame greenhouses deliver clearly lower PAR than Barrel-vault models across 12 months. Taking the Barrel-vault as a reference, the ranges of percentage difference of monthly PAR in A-frame are -14.64~-12.61% (Lhasa), -13.6~-12.46% (Beijing), and -13.71~-12.37% (Yinchuan). The differences in summer tend to be smaller than winter. For the greenhouse with A-frame roof or Barrel-vault roof, Lhasa generally has the higher PAR than Yinchuan and Beijing, while the period from April to August sees a higher PAR in Yinchuan than Beijing and other periods see similar PAR levels between the two locations. PAR peaks at the period from May to July at all locations.

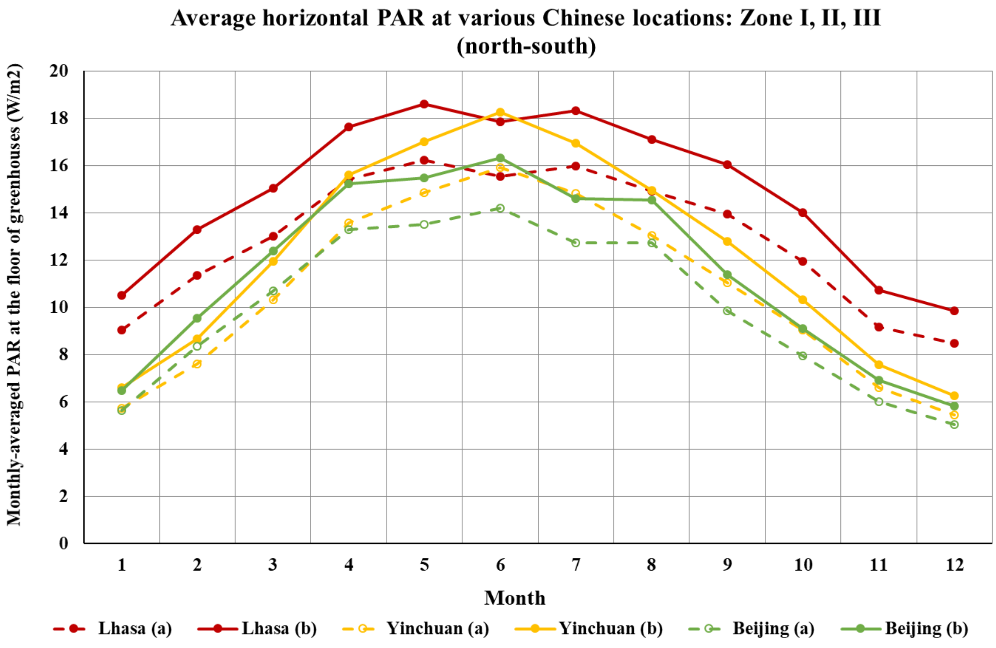

Fig. 5: Monthly-averaged PAR at the floor of two greenhouses (zone I, II and III).

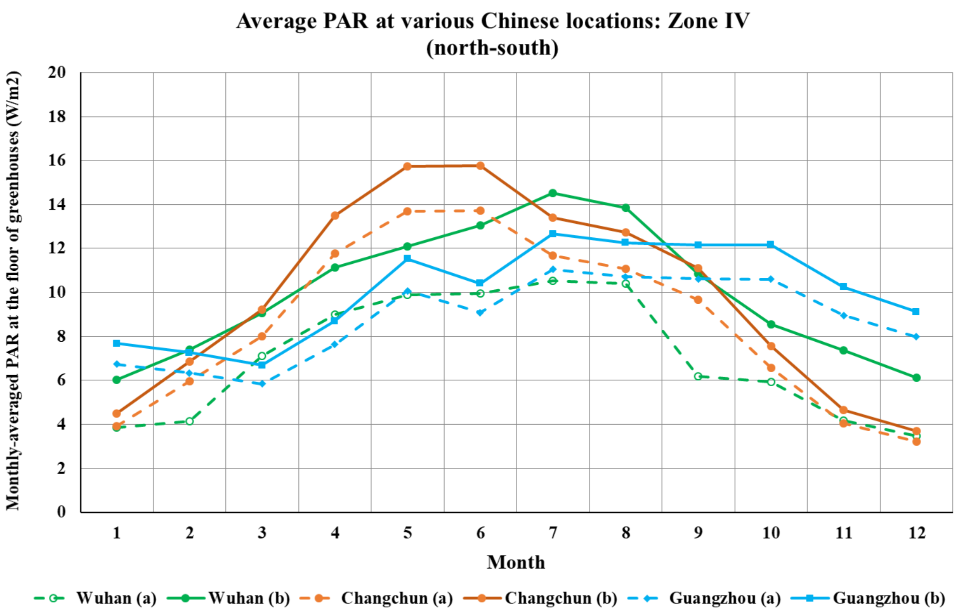

Fig. 6: Monthly-averaged PAR at the floor of two greenhouses (zone IV).

In Figure 6, three zone IV locations (Changchun, Wuhan and Guangzhou) were assessed according to the orientation of north-south. Similar to the orientation of east-west (Figure 3), Changchun, Wuhan and Guangzhou have the PAR peak periods of (May to June), (July to August), and (July to October) respectively. Generally, Barrel-vault greenhouses can give rise to a significantly higher PAR than A-frame models. The ranges of percentage difference (Barrel-vault is the reference) of Changchun, Wuhan and Guangzhou are -13.22~-12.83%, -43.86~-18.43%, -12.78~-12.26% respectively. Interestingly, the largest differences of PAR between two greenhouses occur at the middle latitude (Wuhan), while the high and low latitudes (Changchun and Guangzhou) see similar values.

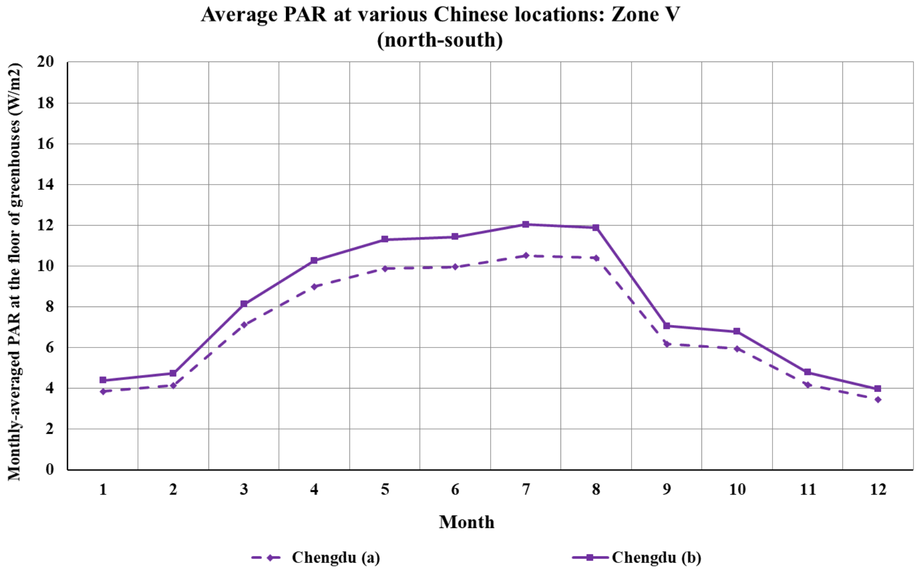

Fig. 7: Monthly-averaged PAR at the floor of two greenhouses (zone V).

Table 3 shows the annual-averaged PAR at seven locations. For A-frame greenhouses, Lhasa has achieved the highest PAR while the lowest PAR can be found at both Wuhan (zone IV) and Chengdu (zone V). Barrel-vault greenhouses can see similar trend as Table 2 (east-west). In general, A-frame roof will deliver lower PAR in greenhouses at all locations.

Tab. 3: Annual-averaged PAR in the two greenhouses (north-south)

Annual-averaged PAR (W/m^2)							
Locations	**Lhasa**	**Yinchuan**	**Beijing**	**Guangzhou**	**Wuhan**	**Changchun**	**Chengdu**
A-frame	12.92	10.67	10.00	8.80	7.05	8.61	7.05
Barrel-vault	14.92	12.25	11.49	10.07	10.00	9.90	8.06

3.3. Comparison between two orientations

In order to further compare the effect of orientation on PAR performances, percentage differences of PAR between two orientations (R_{PAR}) can be calculated by the following equation:

$$R_{PAR} = [1 - \frac{PAR_{(N-S)}}{PAR_{(E-W)}}]100\% \quad \text{(eq. 3)},$$

where, $PAR_{(E\text{-}W)}$ and $PAR_{(N\text{-}S)}$ are monthly-averaged PAR or annual-averaged PAR at the floor of two greenhouses with orientations of east-west and north-south respectively.

Table 4 & 5 give the R_{PAR} values (monthly and annual) in the A-frame and Barrel-vault greenhouses at seven locations. It can found the orientation of east-west can receive at least 40% more annual-average PAR across the floor in two greenhouses than north-west. In Table 4, for annual performances, Wuhan (zone IV) has the largest R_{PAR} value whilst no big differences of the value can be found at other six locations. At the locations in zone I, II, II, and IV, winter can bring in relatively higher PAR differences (R_{PAR}) than summer. However, the differences of R_{PAR} between cold and warm seasons could be unclear in Chengdu (zone V). Compared with Table 4, Table 5 (Barrel-vault roof) displays some differences: there are no significant differences of R_{PAR} found at all seven locations. The R_{PAR} values with A-frame roof are relatively higher than those with Barrel-vault roof, which could mean that the later has a lower sensitivity to the orientation than the former. Except for Chengdu, other locations have higher R_{PAR} values in winter than summer.

Tab. 4: Percentage differences of PAR between two orientations (A-frame)

R_{PAR} (%)													
	Monthly												**Annual**
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	
Lhasa	54.50	54.02	52.35	51.23	50.34	49.87	49.99	50.81	51.96	53.64	54.35	54.66	52.01
Yinchuan	55.15	53.78	53.27	52.39	51.55	51.19	51.41	51.93	53.04	53.58	54.64	55.48	52.68
Beijing	56.35	54.67	53.86	52.66	52.10	52.03	52.03	52.39	53.45	54.08	55.40	56.01	53.31
Guangzhou	53.66	53.03	52.67	52.36	52.17	52.06	52.21	51.96	52.45	52.93	53.58	53.92	52.71
Wuhan	66.52	70.18	57.44	56.09	55.03	57.93	59.74	58.96	69.09	62.92	70.15	70.34	61.79
Changchun	56.93	54.99	53.80	52.82	52.28	53.47	52.53	52.55	53.55	54.37	56.03	57.36	53.61
Chengdu	53.71	53.08	52.67	52.18	51.67	51.32	51.50	51.81	52.61	53.14	53.49	53.40	52.27

Tab. 5: Percentage differences of PAR between two orientations (Barrel-vault)

R_{PAR} (%)													
	Monthly												**Annual**
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	
Lhasa	44.07	43.63	42.63	42.48	41.68	41.13	41.24	42.06	42.62	43.40	43.59	43.97	42.53
Yinchuan	45.94	44.56	42.43	43.26	43.19	42.13	42.53	43.15	42.25	43.99	45.41	46.30	43.37
Beijing	46.52	45.59	44.95	44.10	43.32	43.17	43.20	43.82	44.65	45.14	46.13	46.74	44.41
Guangzhou	44.77	44.08	43.65	43.68	43.56	43.30	43.51	43.33	43.15	43.92	44.55	44.63	43.81
Wuhan	45.04	44.34	42.82	43.65	43.35	43.31	43.04	43.63	42.94	43.91	44.89	45.25	43.66
Changchun	48.18	45.92	43.51	42.76	43.12	43.50	43.70	42.84	43.38	45.00	47.10	48.63	44.04
Chengdu	44.75	44.05	43.43	43.47	42.95	42.53	43.21	44.26	43.40	43.97	44.44	44.38	43.56

4. Discussion and conclusion

Based on the results above, several key findings are discussed as follows.

1. PAR availabilities (solar irradiance) in the greenhouses are significantly determined by the location (latitude) and climate conditions (daylight climate zone) in China. In this study, the applications of RADIANCE and local weather data have led to an analysis under real sky conditions (including all possible sky types). In general, the overall PAR availability receives higher impact from climate conditions, while the latitude could clearly affect the peak time of PAR. This study indicates that a climate-based analysis (using daylight climate zones and real weather data) has be proved as more useful and practical than the methods based on clear sky and solar geometries (Kurata, 1993; Farkas et al., 2001; Sethi, 2009).

2. Compared with the orientation of north-south, the orientation of east-west can deliver much higher PAR levels in both A-frame and Barrel-vault greenhouses across various locations in China (at least 40% more). This finding well agreed with the studies conducted in various countries outside of China (Sethi, 2009; Mobtaker et al., 2016;

Kendirli, 2006). The longitudinal orientation of east to west is an optimal design solution in greenhouses in terms of PAR availability, which will not vary in latitudes and climate conditions.

3. With the orientation of east-west, A-frame greenhouses can deliver a slightly higher PAR availability than Barrel-vault greenhouses, especially for the locations within the daylight climate zones of I, II and III. On the other hand, the orientation of north-south can lead to clearly lower PAR availability in A-frame greenhouses. These could be explained by the facts that the solar beam transmittance is higher at the slope of A-frame roof than the curved surface of Barrel-vault roof, whilst the section of Barrel-vault roof has a larger area to get more solar beam transmittance in than the section of A-frame (Sharples & Lash, 2007).

Given the discussions above, a protocol to support the design of greenhouse could be considered: 1) Analysis of climate conditions including solar irradiations and latitudes; 2) Analysis of possible orientations of greenhouse plan; 3) Planning the roof structures of greenhouse based on the climates and orientations; 4) If applicable, implementing a PAR analysis of an early-stage plan; 5) If applicable, implementing a comprehensive analysis of greenhouse plan, taking into account more environmental factors (PAR is one of most important issues); 6) Decision-making process.

Limitations and future works: This study only investigated two typical greenhouse roofs and two cardinal orientations. More parametric studies, including non-cardinal orientations, complex roof configurations, obstructions, etc., will be conducted in the future work.

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