Preprints.org

Article

Not peer-reviewed version

Analysis of the Influence of Grating Plate on the Internal Illumination Uniformity of Zigzag Photovoltaic Greenhouse

Baolong Wang , Yehua Si , Jian Liu *

Posted Date: 26 December 2023

doi: 10.20944/preprints202312.1932.v1

Keywords: Zigzag photovoltaic greenhouse; Grating plates; Light intensity; Illumination uniformity

Article

Analysis of the Influence of Grating Plate on the Internal Illumination Uniformity of Zigzag Photovoltaic Greenhouse

Baolong Wang [1,2,†], Yehua Si [2,†] and Jian Liu [2,*]

[1] Sanya Institute of Breeding and Multiplication, Sanya 572025 ,China ;wangbaolong@hainanu.edu.cn (B.W.); 20213007177@hainanu.edu.cn(Y.S.)
[2] School of Tropical Agriculture and Forestry, Danzhou 571737, China
* Correspondence: liujian99@hainanu.edu.cn
† These authors contributed equally to this work.

Abstract: As one of the main projects of facility agriculture promotion, the photovoltaic greenhouse has the problems of photovoltaic power generation competing for light with crop production, strong indoor chiaroscuro, and uneven light distribution. The internal light uniformity is tested by a zigzag greenhouse model to compare the light transmission effects of different light-transmitting materials applied to photovoltaic greenhouses. 20 line\inch 3mm and 30 line\inch 3mm, 40 line\inch 2mm, 25 line\inch 4mm grating plates, 2mm, and 3mm thick ordinary glass were used as light transmitting components, and the light intensity and light uniformity in the greenhouse were the measurement indicators. The results show that the use of grating plates as covering material can improve the light intensity at the intersection of light and dark, but the overall light transmittance is not as good as glass, because it is plastic which is easy to age with low light transmittance. It can also improve the use of land under the shade of photovoltaic modules to provide a better growth environment for crops. Test results show that the use of a 2mm thick 40-line grating plate can maximize the light intensity of the greenhouse, and the peak value can reach 69336 Lx. In sunny weather, the light intensity from point G to point I in the greenhouse is greater than 20,000 Lx, and the light environment in other areas is between 5,000 Lx and 20,000 Lx, which is suitable for planting shade-loving crops.

Keywords: zigzag photovoltaic greenhouse; grating plates; light intensity; illumination uniformity

1. Introduction

At present, the energy structure at home and abroad is mainly based on fossil fuels. However, fossil fuels are non-renewable energy. With the increasing demand for energy and the continuous exploitation and consumption of fossil energy, it is urgent to develop renewable energies, such as wind power, hydropower, solar energy, etc. Among them, solar energy is the most popular energy, and photovoltaic power generation is one of the main forms of solar energy utilization. Photovoltaic power generation includes rooftop photovoltaic, water photovoltaic, and traditional photovoltaic ground power stations. A photovoltaic greenhouse is an application form of photovoltaic power generation, which is mainly used in agricultural production, especially in areas with limited land resources or lack of power supply. Photovoltaic greenhouse converts solar energy into electricity, which can be directly supplied to lighting, heating, ventilation, and other equipment and automation systems in the greenhouse, and can also be connected to power grids [1]. Photovoltaic greenhouse technology is closely related to sustainable development. The use of clean energy can reduce the dependence on traditional power grids, use less fossil energy, improve the utilization rate of solar energy, and contribute to environmental protection and sustainable economic development. In addition, when used properly, photovoltaic greenhouse can also provide a good growing environment, such as suitable temperature, light, and ventilation conditions, to promote the growth of crops and increase yields. However, the shading of photovoltaic modules will inevitably reduce the light intensity in the greenhouse, change the light distribution characteristics in the greenhouse, and affect the growth of plants. At present, the scattering film is mainly used as the light-transmitting component, which can expand the illumination area and improve the light distribution characteristics in the greenhouse, but the effect is not satisfactory. There are still some challenges in photovoltaic greenhouse technology, such as the cost, efficiency, and reliability of photovoltaic panels, as well as technical issues in terms of light uniformity, ventilation, and temperature control inside the greenhouse, and solving these challenges requires continuous technological innovations and improvements.

In order to solve the problem of uneven light distribution in photovoltaic greenhouses caused by the shading of photovoltaic cell modules from the perspective of light-transmitting modules on the greenhouse roof, the grating plates with high scattering and high transmittance used as light-transmitting modules to improve the light distribution in zigzag photovoltaic greenhouses can effectively improve the light intensity in the greenhouse [2]. Liu Chengyu, et al. [3] pointed out that a large number of experimental studies have been carried out on photovoltaic greenhouses. The experimental results of these studies have summarized the problems and opinions regarding the research and development of photovoltaic greenhouses, as well as the relatively low utilization rate of light energy and the high maintenance price of photovoltaic equipment, and it is particularly important to ensure that the light uniformity in the photovoltaic greenhouse is suitable for plant growth and ensure the thermal insulation function of the greenhouse while not affecting the operation of photovoltaic power generation in the greenhouse [4]。

In this study, grating panels with different thicknesses and number of lines were used as photovoltaic greenhouse light-transmitting modules, and ordinary glass was used as the control to test the light intensity and uniformity in the greenhouse. The use of grating panels as greenhouse roof covering material was evaluated.

As shown in Figure 1, the grating plate is a plastic material with one side extruded into a cylindrical line and one side as a complete plane, and the cylindrical line spacing is equal to that called "grating". The light transmittance of the grating plate used in this experiment is 93.77%, and the spectroscopic light waves of the grating will be diffracted at each slit, and the light waves diffracted through all slits will interfere to form interference fringes and be localized to infinity. When sunlight is incident on the grating plate, the area that can be irradiated by the light passing through the grating plate is greater than the area of the grating plate itself [5]. As a polymer light scattering material, the grating plate converts the parallel direct light into an isotropic surface light source and expands the illumination area, thus solving the problem of illumination uniformity to a certain extent.

Figure 1. Grating plate.

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 26 December 2023 doi:10.20944/preprints202312.1932.v1

2. Materials

2.1. Zigzag photovoltaic greenhouse

The test greenhouse is a zigzag photovoltaic greenhouse [WS-GFJ-X.X(HD)] developed from the patented shed greenhouse of Professor Liu Jian of Hainan University: A Combined Photovoltaic Greenhouse Roof Structure (ZL201621352420.7) [6]. The span of the photovoltaic greenhouse is 5.5-7.5m, the bay is 4m, the shoulder height is 2.2-2.5m, and the top height is 3.4-3.7m, as shown in Figures 2 and 3.

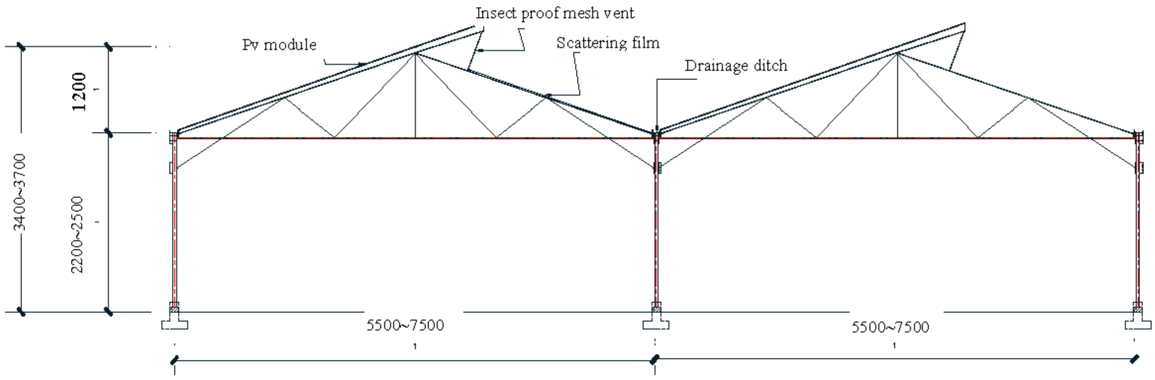


Figure 2. Schematic diagram of zigzag photovoltaic greenhouse structure (mm).

Figure 3. A real picture of the zigzag photovoltaic greenhouse.

Combined with the climatic characteristics of the Hainan hot area and the needs of the solar and thermal environment of vegetable planting, the standard sawtooth photovoltaic vegetable greenhouse reasonably optimizes the layout of the roof structure and uses photovoltaic modules as roof covering materials to replace some traditional transparent covering materials such as films. Because of its reasonable structure, the ground planting utilization rate becomes higher, and the light and heat environment are more suitable, which can achieve the goal of not reducing the output of vegetable production compared with open field planting, and can ensure the uninterrupted production of photovoltaic vegetable greenhouses [7].

The research on indoor lighting problems of zigzag photovoltaic greenhouses mainly focuses on the location of the greenhouse (latitude and longitude, altitude, etc.), orientation, structure, light characteristics of covering materials and enclosure materials (light transmittance, reflectivity, etc.), surrounding features, weather and other factors that have a great impact on the lighting in the

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 26 December 2023 doi:10.20944/preprints202312.1932.v1

greenhouse. The problem of shading and lighting in greenhouses also needs to solve the problem of reasonable distribution of sunlight in crops and photovoltaic power generation, and to maximize the benefits of agriculture and photovoltaic industry.

2.2. Zigzag photovoltaic greenhouse model

The model greenhouse is constructed according to the scale of 1:11 with a span of 500 mm, a column height of 160 mm, and a bay of 600 mm. 20mm×20mm aluminum profiles were used as the model greenhouse skeleton material. The azimuth of the greenhouse is set to due south, and the roof of the south slope is facing the sun [8]. Figures 4–6 shows the structural diagram and the physical drawing of the greenhouse model, the column and the roof beam of the model are connected by a rotating corner chain, the column and the beam part are connected by a vertical corner piece, the roof beam and the roof beam are connected by a vertical turning angle piece, and are covered with 40 mesh insect nets around it.

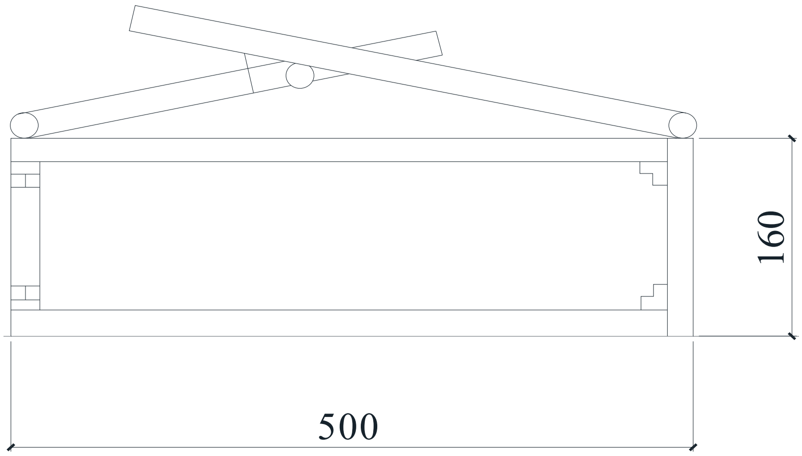


Figure 4. Schematic diagram of greenhouse model structure (mm).

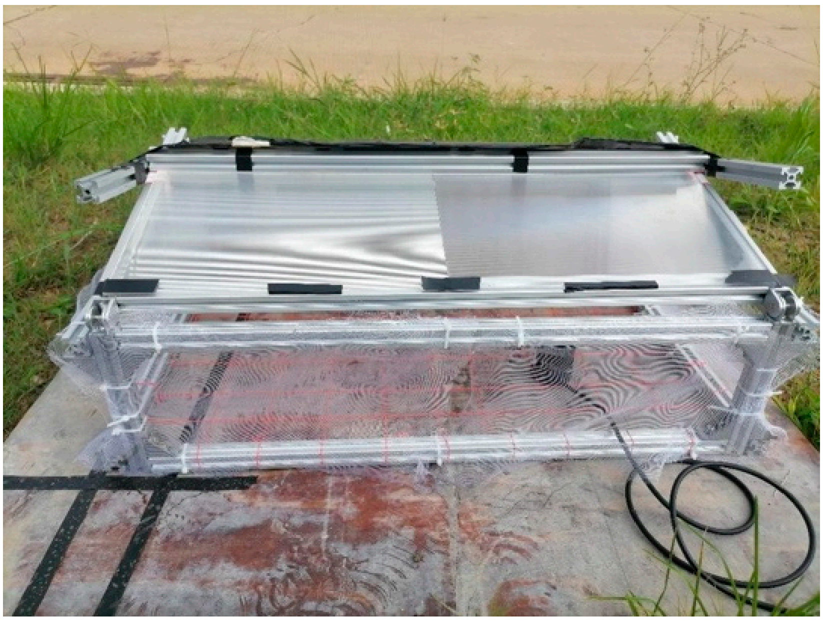


Figure 5. North end of the field experiment model (insect net can be opened).

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 26 December 2023 doi:10.20944/preprints202312.1932.v1

Figure 6. Side view of the field experiment model.

3. Experimental design and field management

3.1. Selection of test measurement sites

As shown in Figure 7, six lines were set in the east-west direction of the greenhouse, which were respectively recorded as N1 to N6 at the distance from the 5.5.cm, 14.50cm, 23.50cm, 32.50cm, 41.50cm, and 50.50cm of the gable on the east side. There were nine points on each line, which were evenly distributed in the east-west direction and north-south direction from the inside of the greenhouse. The distances were 3.0cm, 8.0cm, 13.0cm, 18.0cm, 23.0cm, 28.0cm, 33.0cm, 38.0cm, and 43.0cm, which were recorded as point A to point I.

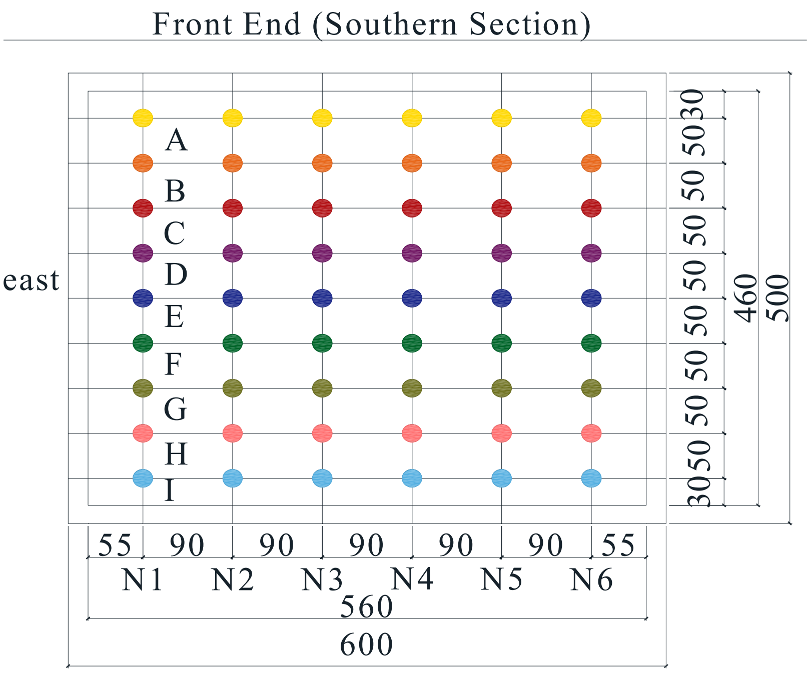


Figure 7. Schematic diagram of the front and back sections of the light intensity measurement point (mm).

3.2. Experimental time

The outdoor experiment was conducted at the Agricultural Science Base of Danzhou Campus of Hainan University (19°11'N, 108°56'E) from 10:00 to 16:00 on June 1, 2023 (sunny) and from 10:00 to 16:00 on June 2 (sunny).

$$U_0=E_{min}/E_{av} \quad (1)$$

3.3. Experimental process

First of all, according to the formula mentioned in the *Environmental Engineering of Facility Agriculture* edited by Zou Zhirong and Shao Xiaohou [9]: the number of inclination angles of the south roof β>90°-40°-*α*=50°-*α* (*α* is the solar altitude angle at a certain time), the latitude of Danzhou at this time is 19°, and the solar regression movement from June 1 to 2 is moving from south to north, the days are getting longer, and the sunshine time in the northern hemisphere is all lengthened, we assume that the solar altitude angle is 38°, and 12° is selected as the inclination angle of the south roof; secondly, according to the test schedule in Table 1, the relationship between the light transmitting components of different specifications and the light transmission of the point zone was tested one by one. Finally, Origin64 software was used for data analysis and comparison [10].

Table 1. Experimental arrangement.

Roof inclination angle\。	Point	Translucent components	Data Acquisition (Time)
12	A	Translucent glass:	10：30
	B	2mm glass	11：30
	C	3mm glass	12：00
	D	Grating plate:	12：30
	E	20 line\inch 3mm	13：30
	F	30line\inch3mm	14：30
	G	25 line\inch 4mm	
	H	40 line\inch2mm	
	I		

4. Results

4.1. Light distribution characteristics of the corresponding area of the light-transmitting material in the greenhouse

4.1.1. Characteristics of light distribution in the north-south direction of the greenhouse

As shown in Figure 8 below, the largest theoretical solar altitude angle is at 90 degrees when not considering the difference in the Tropic of Capricorn, and Figure 8 shows the north-south light distribution characteristics of the corresponding area of each material during this time, which is at 12:00. Combined with the analysis method of Li H et al. [11], the relevant lighting characteristics were analyzed by the one-day variation law and the significance Duncan analysis was performed on this basis.

On the whole, the light intensity from point A to point E is significantly lower than that from point F to point I, and the highest light intensity is at point G or H. In the southern area, the scattered light entering from the south increases the illumination intensity of point A, which is obviously

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 26 December 2023 doi:10.20944/preprints202312.1932.v1

higher than that of points B and C. In the middle area, the growth trend from point D to point E is lower than that from point E to point F, and the illuminance of glass at point F is greater than that of grating plate. The light intensity from point G to point H in the back-end area is generally greater than that of the grating plate, while point I is the opposite [12].

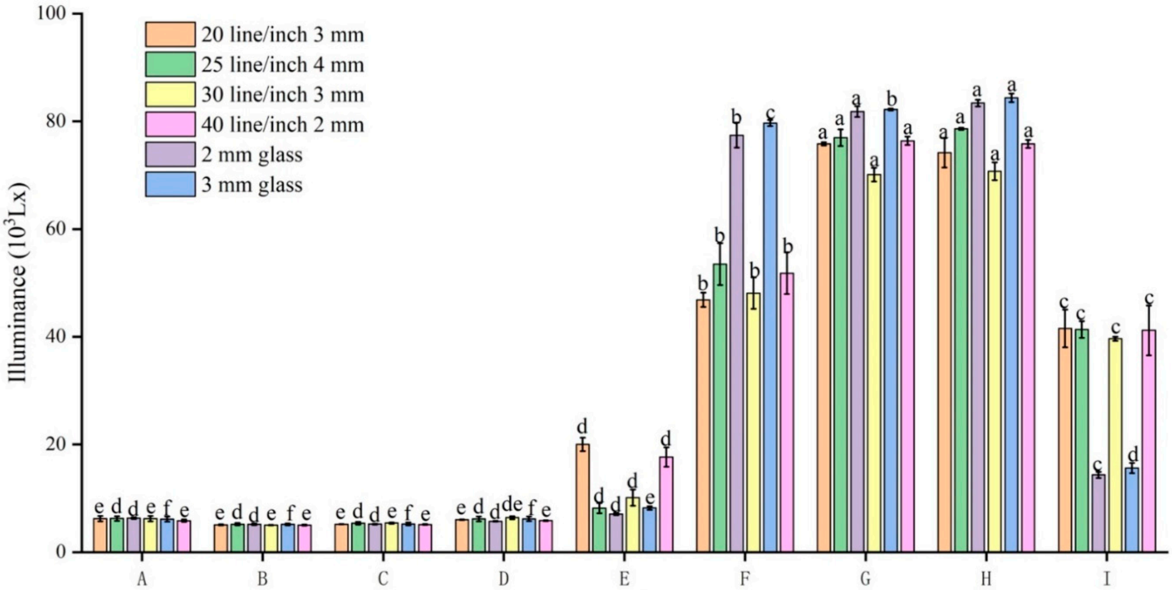


Figure 8. 12:00 a.m. The light distribution of each point in the north-south direction of the corresponding area in each plate greenhouse.

4.1.2. North-south light distribution in the greenhouse

The distribution of light intensity in the north-south direction in different time periods in the greenhouse is shown in Figures 9–13, and in general, the influence of cloud cover is excluded Choab N et al. [13] Bulik, T, Piacentini et al. [14] The distribution trend of light intensity in the north-south direction of each light transmitting material in each time period is as follows: the light intensity from point B to point G or H gradually increases and reaches the peak value. According to the analysis methods of Igoe, D, Turner et al. [15], and Ayet A et al. [16], it is inferred that point A is affected by the scattered light from the ground to the south, and the light intensity is greater than that of point B. The light intensity of glass as a light-transmitting component of a greenhouse is generally greater than that of grating panels [17].

 doi:10.20944/preprints202312.1932.v1

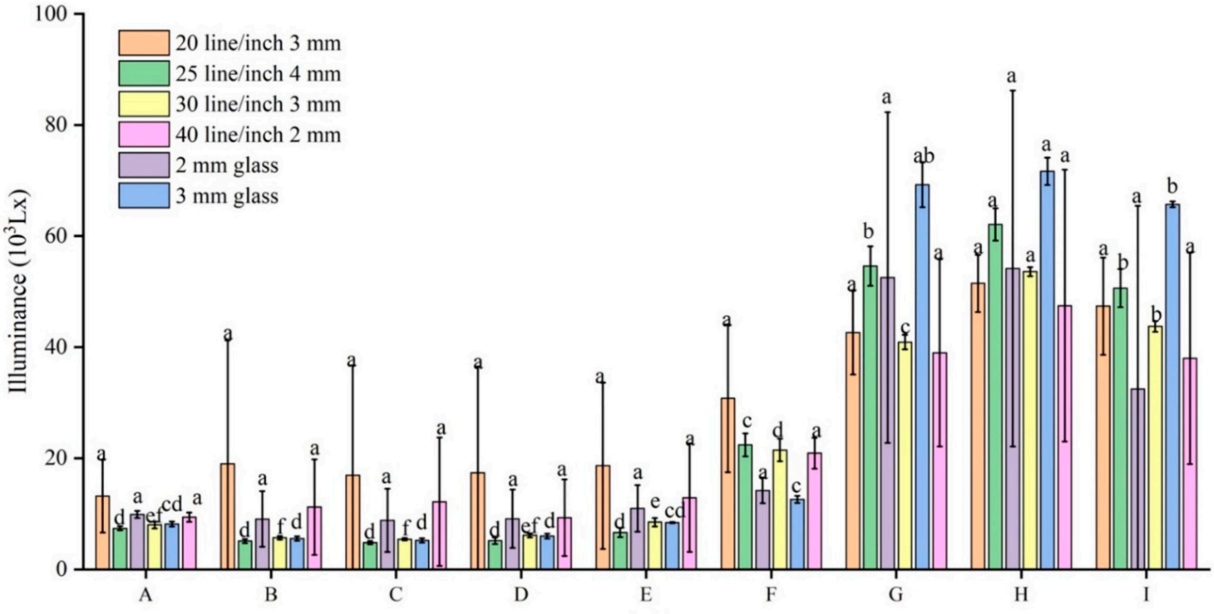


Figure 9. 10:30 a.m. Average light intensity at each point.

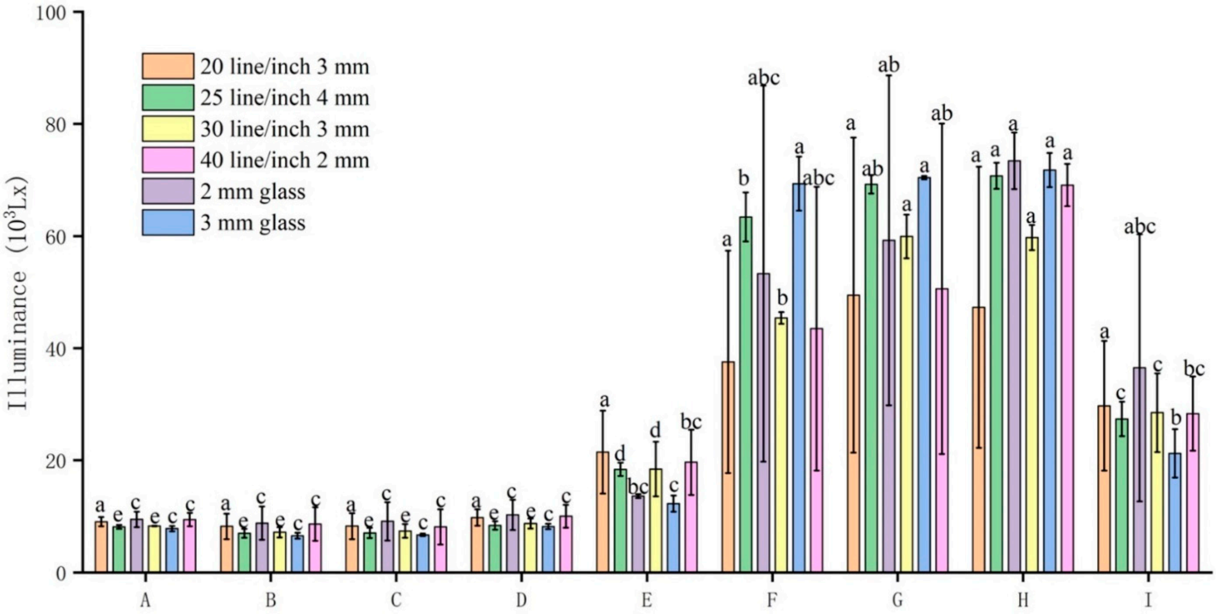


Figure 10. 11:30 a.m. Average light intensity at each point.

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 26 December 2023 doi:10.20944/preprints202312.1932.v1

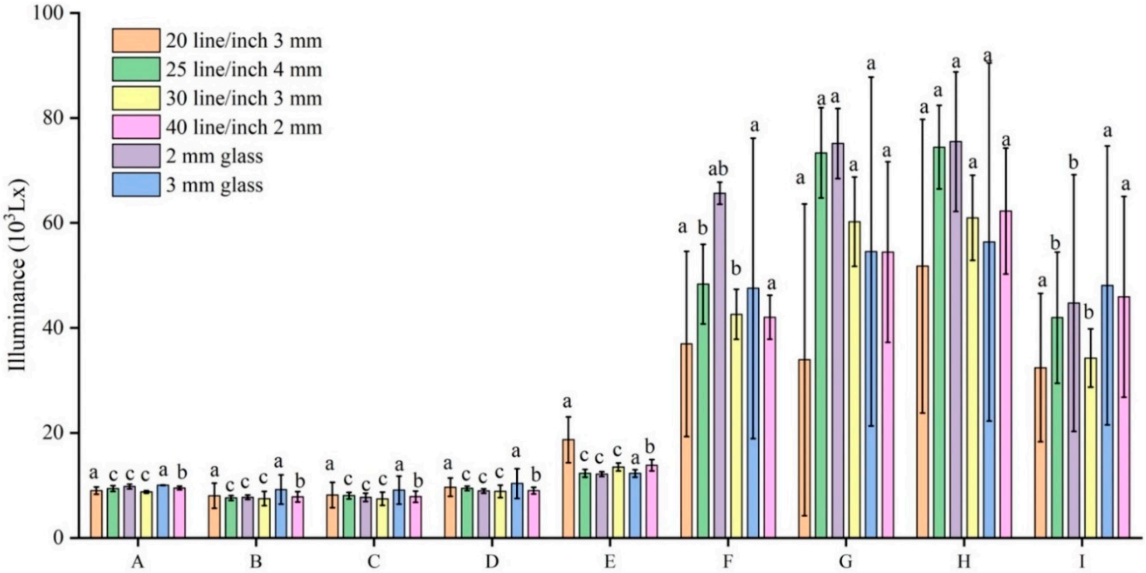


Figure 11. 12:30 p.m. Average light intensity at each point.

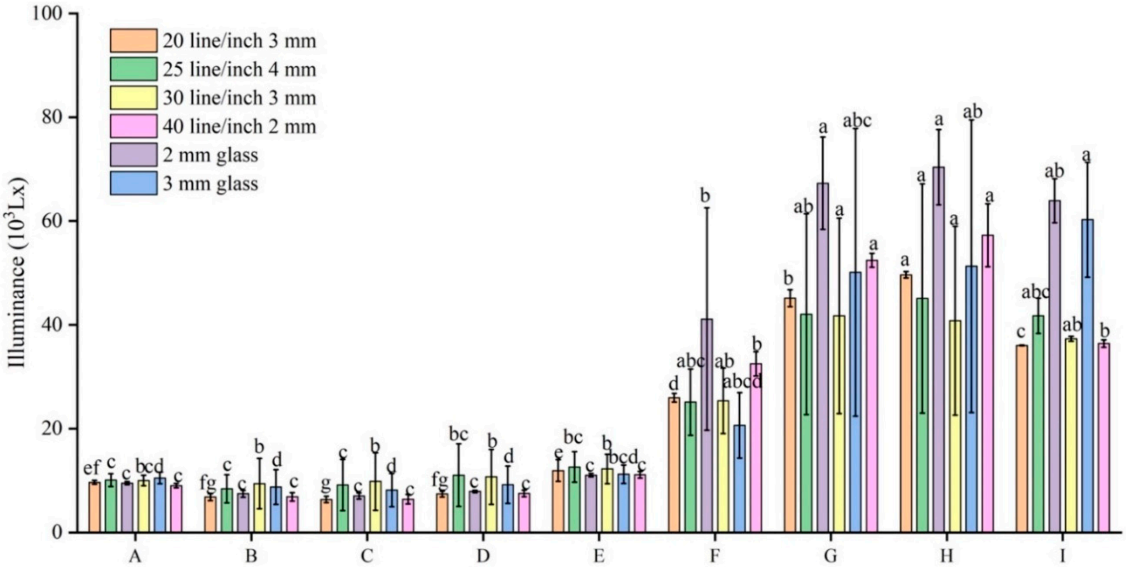


Figure 12. 13:30 p.m. Average light intensity at each point.

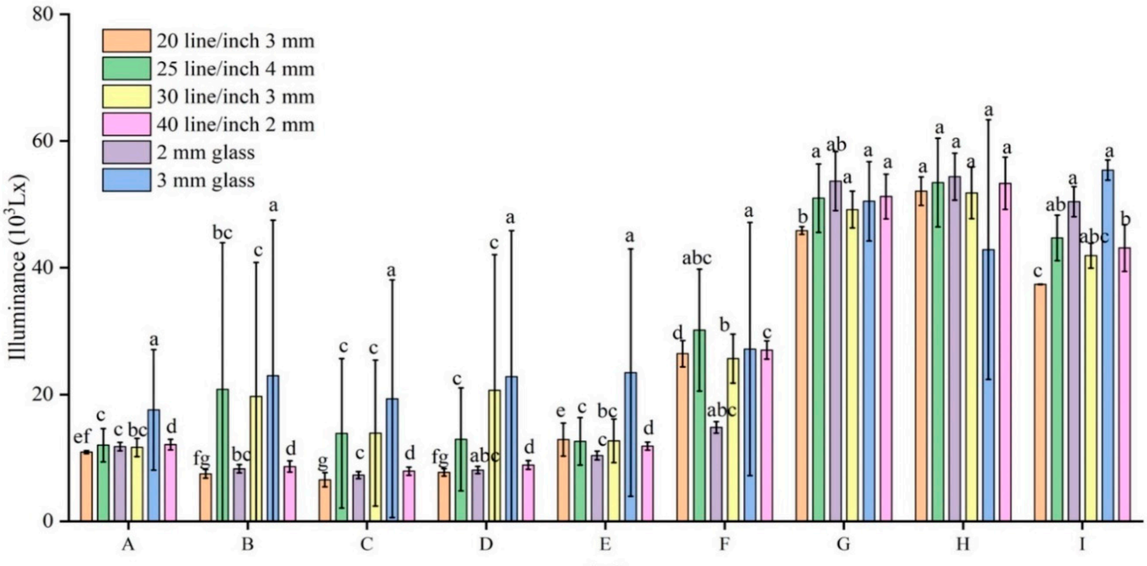
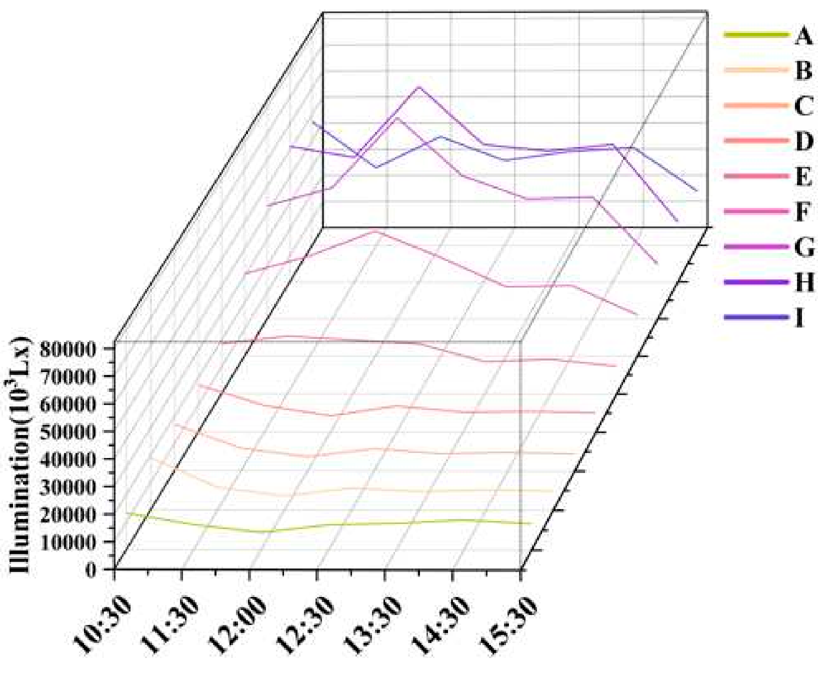


Figure 13. 14:30 p.m. Average light intensity at each point.

4.2. Data processing and analysis

As shown in Figures 14–19, the variation of the illuminance of each material over time is distributed over time and appears in a "W" shape assuming that cloud interference is excluded [18,19]. The illumination intensity of each dot zone of each material will reach a small peak at 12:30 because the solar altitude angle is the highest and the light intensity is strongest at noon, and the illumination of each dot zone at 11:30 and 13:30 is lower than the value of 12:30. The illumination of each point at 10:30 and 14:30 is greater than that at 11:30 and 13:30, because the light measured at the N1 or N6 lines at the measurement points in the greenhouse is directly through the insect net and is not refracted through the light transmitting element and obscured by the greenhouse skeleton [20]. In fact, the light intensity of the outdoors changes at any time [21], the cloud layer is always moving, and the measurement process takes time, which makes the measurement results not exactly the same as the conjecture. Meanwhile, considering the evaporation of water vapor is the highest when the solar altitude angle at noon, the blocking of water vapor will also affect the measurement results [22,26–28].



Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 26 December 2023 doi:10.20944/preprints202312.1932.v1

Figure 14. The average illumination intensity of each point of the 20line\inch 3mm thick grating plate at different times (Illuminance at different time points from point A to point I).

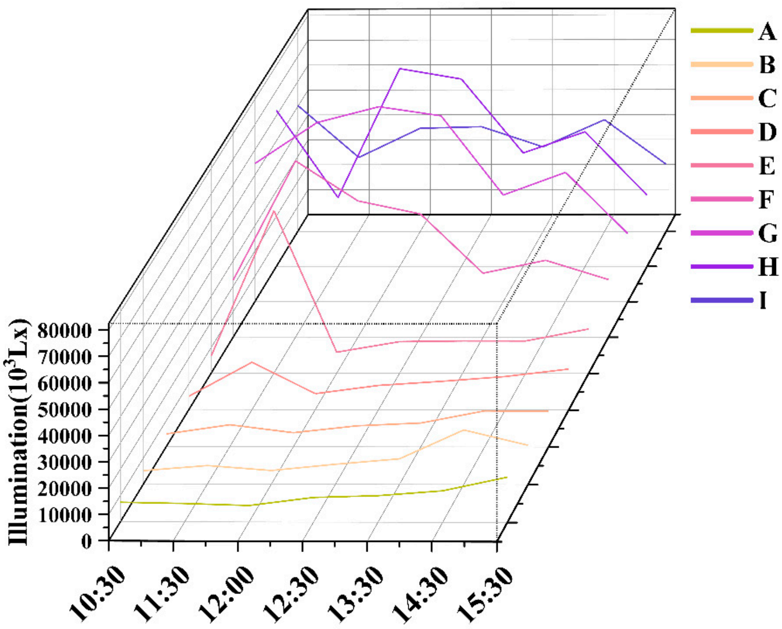


Figure 15. The average illumination intensity of each point of the 25line\inch 4mm thick grating plate at different times (Illuminance at different time points from point A to point I).

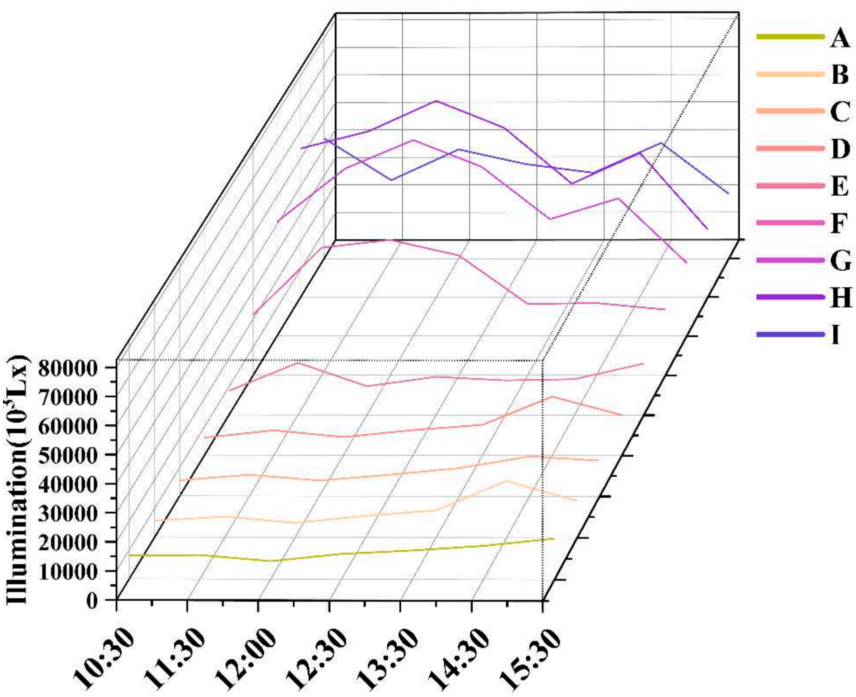


Figure 16. The average illumination intensity of each point of the 30line\inch 3mm thick grating plate at different times (Illuminance at different time points from point A to point I).

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 26 December 2023 doi:10.20944/preprints202312.1932.v1

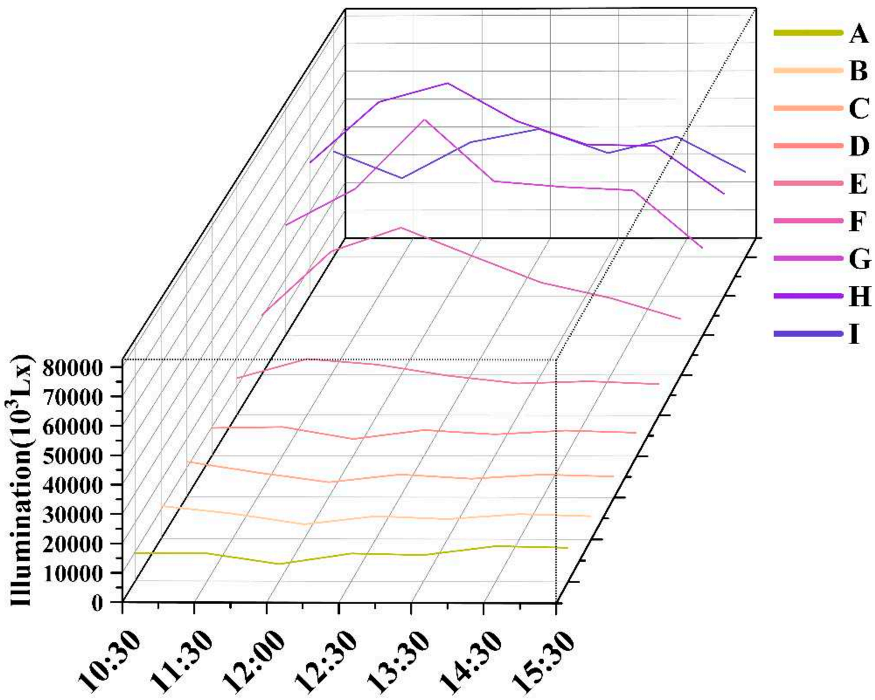


Figure 17. The average illumination intensity of each point of the 40line\inch 2mm thick grating plate at different times (Illuminance at different time points from point A to point I).

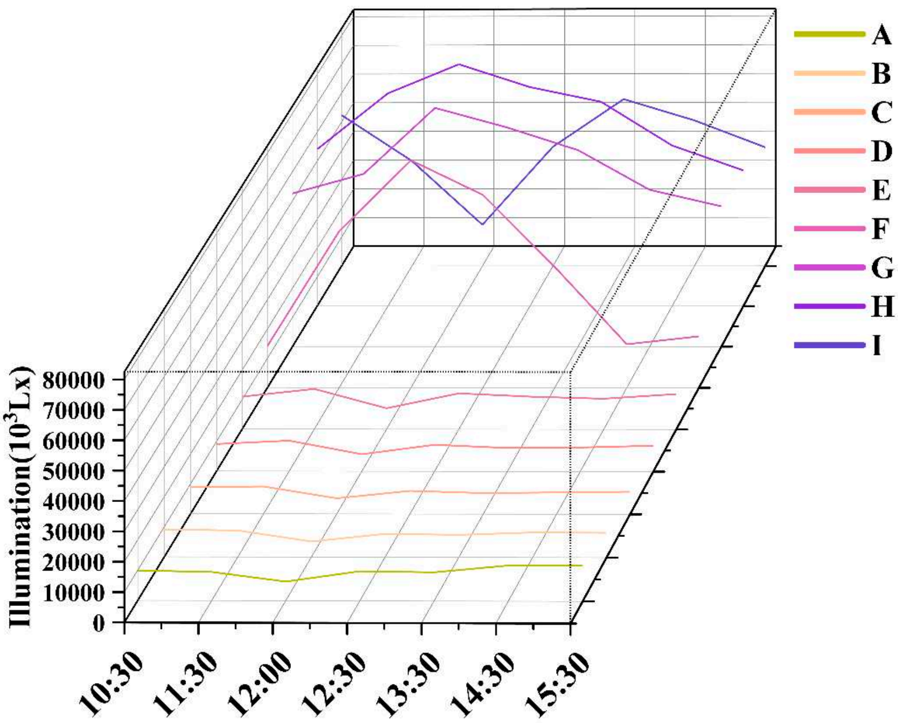


Figure 18. The average light intensity of each dot band of 2 mm thick glass at different time (Illuminance at different time points from point A to point I).

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 26 December 2023 doi:10.20944/preprints202312.1932.v1

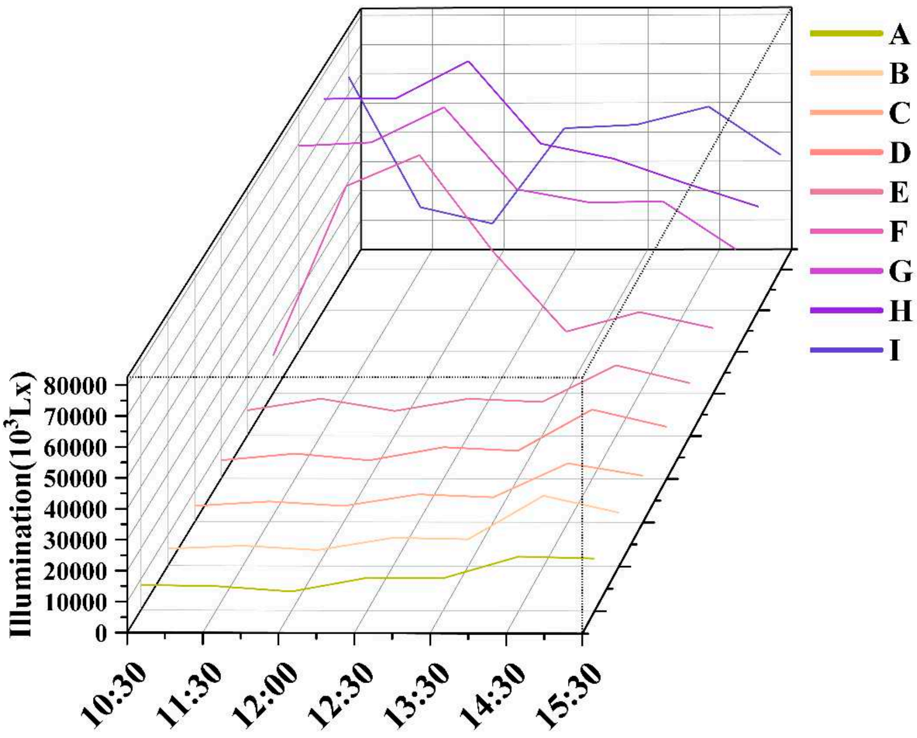


Figure 19. The average light intensity of each dot band of 3 mm thick glass at different time (Illuminance at different time points from point A to point I).

4.3. Light uniformity in the greenhouse

4.3.1. Light uniformity and variation coefficient

Tables 2–7 shows the light uniformity and variation coefficient in the model greenhouse at different time periods [23] when the grating plate and glass are used as light-transmitting components. The data varied a lot due to the different measurement times of each point and the rapid change of the atmospheric cloud layer [24]. The results of data processing are as follows:

Table 2. Light uniformity and variation coefficient of 20line\inch 3mm grating transmittance component.

Time	20line\inch 3mm	A	B	C	D	E	F	G	H	I
10:30	Average(Lux)	13204	19023	16967	17407	18648	30788	42619	51477	47391
	Variance	6540	22226	19731	19084	14952	13310	7521	5145	8753
	Cv	0.495	1.168	1.163	1.096	0.802	0.432	0.176	0.100	0.185
	Illumination(%)	68.27	29.86	31.12	33.93	47.29	69.89	88.47	93.12	87.35
11:30	Average(Lux)	9048	8280	8264	9791	21463	37555	49452	43701	29714
	Variance	829	2293	2334	1469	7380	19831	28091	25080	11564
	Cv	0.092	0.279	0.282	0.150	0.344	0.528	0.568	0.530	0.389
	Illumination(%)	94.48	81.46	81.24	86.97	61.38	39.35	34.41	38.78	55.07
12:30	Average(Lux)	9028	8038	8154	9658	18696	36957	53929	52073	32435
	Variance	691	2395	2417	1724	4369	17637	30407	29221	14127
	Cv	0.077	0.298	0.296	0.178	0.234	0.477	0.564	0.542	0.436
	Illumination(%)	94.50	79.81	81.84	89.51	75.73	45.28	35.27	37.43	50.33

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 26 December 2023 doi:10.20944/preprints202312.1932.v1

13:30	Average(Lux)	9658	6819	6363	7419	11937	25959	45146	46941	35807
	Variance	371	661	623	557	2081	847	1631	620	403
	Cv	0.038	0.097	0.098	0.075	0.174	0.033	0.036	0.012	0.011
	Illumination(%)	97.25	90.36	94.24	95.22	80.80	96.31	96.94	98.56	98.71
14:30	Average(Lux)	10925	7501	6888	7732	12879	26428	45861	52064	37354
	Variance	236	672	680	587	2602	2088	598	2253	44
	Cv	0.022	0.090	0.099	0.076	0.202	0.079	0.013	0.043	0.001
	Illumination(%)	98.40	91.94	93.22	94.86	79.45	91.40	99.02	95.20	99.92

In Table 2, the illumination uniformity of the 20-line 3mm thick grating plate as the light transmitting module from point A to point I and from 10:30 to 14:30 increased with time, the variation coefficient increased with time, and the variance decreased with the increase of time.

In Table 3, the illumination uniformity of the 25-line 4mm thick grating plate as the light transmitting module from point A to point I and from 10:30 to 14:30 decreased with the increase of time, the variation coefficient increased with the increase of time, the variance increased with the increase of time, the average point G, point H and point I decreased with the increase of time, and the other points increased with the increase of time.

Table 3. Light uniformity and variation coefficient of 25line\inch 4mm grating transmittance component.

Time	25line\inch 4mm	A	B	C	D	E	F	G	H	I
10:30	Average(Lux)	7396	5065	4822	5164	6655	22408	54588	62107	50615
	Variance	355	339	292	612	845	2064	3541	2908	3423
	Cv	0.048	0.067	0.060	0.119	0.127	0.092	0.065	0.047	0.068
	Illumination(%)	95.54	92.42	93.06	87.17	85.35	94.28	94.56	95.85	93.81
11:30	Average(Lux)	8112	6979	7042	8397	18387	63385	69224	70738	27373
	Variance	347	800	918	745	1173	4378	1649	2320	3084
	Cv	0.043	0.115	0.130	0.089	0.064	0.069	0.024	0.033	0.113
	Illumination(%)	96.59	90.7	89.51	92.99	95.94	92.03	97.35	96.22	87.24
12:30	Average(Lux)	9381	7627	8062	9429	12317	48343	73348	74430	41962
	Variance	540	468	615	412	755	7606	8581	7972	12486
	Cv	0.058	0.061	0.076	0.044	0.061	0.157	0.117	0.107	0.298
	Illumination(%)	94.52	95.11	94.92	95.22	94.04	83.84	87.28	88.4	65.64
13:30	Average(Lux)	10104	9750	9164	11042	12616	25106	42049	45063	33875
	Variance	1211	4999	4936	6048	2943	6374	19338	22079	13807
	Cv	0.120	0.513	0.539	0.548	0.233	0.254	0.460	0.490	0.408
	Illumination(%)	91.56	69.21	64.09	64.40	81.90	70.71	47.25	44.30	53.65
14:30	Average(Lux)	12001	20822	13874	12921	12601	30164	50966	53427	44685
	Variance	2623	23121	11788	8119	3735	9618	5415	6994	3589
	Cv	0.219	1.110	0.850	0.628	0.296	0.319	0.106	0.131	0.080
	Illumination(%)	82.33	34.12	49.32	59.76	78.10	79.42	87.79	85.88	92.01

In Table 4, the illumination uniformity of the 30-line 3mm thick grating plate as the light transmitting module from point A to point I and from 10:30 to 14:30 decreased with the increase of

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 26 December 2023 doi:10.20944/preprints202312.1932.v1

time, the variation coefficient increased with time, the variance increased with the increase of time, and the variance increased with the increase of time.

Table 4. Light uniformity and variation coefficient of 30line\inch 3mm grating transmittance component.

Time	30line\inch 3mm	A	B	C	D	E	F	G	H	I
10:30	Average(Lux)	8011	5681	5429	6154	8516	21483	40911	53604	43729
	Variance	623	314	221	369	762	2041	1320	810	943
	Cv	0.078	0.055	0.041	0.060	0.089	0.095	0.032	0.015	0.022
	Illumination(%)	91.18	93.62	95.44	94.21	93.37	94.32	97.12	98.94	97.83
11:30	Average(Lux)	8284	7163	7400	8724	18439	45389	59922	59721	28496
	Variance	32	910	1243	910	4871	1065	3915	2257	7023
	Cv	0.004	0.127	0.168	0.104	0.264	0.023	0.065	0.038	0.246
	Illumination(%)	99.76	92.24	88.06	93.97	74.35	97.44	92.46	95.64	74.01
12:30	Average(Lux)	8766	7496	7453	8850	13514	42574	60516	60966	34265
	Variance	257	1370	1240	1178	743	4757	8019	8106	5524
	Cv	0.029	0.183	0.166	0.133	0.055	0.112	0.133	0.133	0.161
	Illumination(%)	97.58	87.98	90.22	91.38	94.96	87.65	85.8	86.97	81.71
13:30	Average(Lux)	10004	9421	9822	10729	12250	25349	41733	40815	31104
	Variance	1007	4856	5564	5299	2827	6305	18830	18184	10752
	Cv	0.101	0.516	0.566	0.494	0.231	0.249	0.451	0.446	0.346
	Illumination(%)	93.45	66.27	63.77	66.86	84.47	73.61	47.95	48.83	60.1
14:30	Average(Lux)	11645	19694	13903	20654	12680	25656	41968	51813	41898
	Variance	1454	21146	11520	21417	3433	3852	2897	4085	1971
	Cv	0.125	1.074	0.829	1.037	0.271	0.150	0.059	0.079	0.047
	Illumination(%)	92.41	35.91	48.63	37.28	80.91	84.56	95.57	91.14	96.06

In Table 5, the illumination uniformity of the 40-line 2mm thick grating plate as the light transmitting module from point A to point I and from 10:30 to 14:30 increased with time, the variation coefficient decreased with the increase of time, and the variance decreased with the increase of time.

Table 5. Light uniformity and variation coefficient of 40line\inch 2mm grating transmittance component.

Time	40line\inch 2mm	A	B	C	D	E	F	G	H	I
10:30	Average(Lux)	9405	11212	12172	9641	12899	20918	38975	47467	37986
	Variance	845	8610	11568	6609	9737	2795	16851	24483	19033
	Cv	0.091	0.768	0.950	0.686	0.755	0.134	0.432	0.516	0.501
	Illumination(%)	90.85	50.88	41.87	56.51	50.87	85.18	50.30	40.44	42.14
11:30	Average(Lux)	9427	8627	8439	10027	19644	43479	51796	69087	28332
	Variance	1190	2989	2872	2065	5843	25311	30460	3758	6618
	Cv	0.126	0.346	0.340	0.206	0.297	0.582	0.588	0.054	0.234
	Illumination(%)	91.34	78.53	78.16	86.61	66.10	32.85	32.10	94.25	73.18
	Average(Lux)	9503	7830	7856	9000	13836	42032	54445	62260	45913

12:30	Variance	348	1001	1058	655	1104	4201	17210	12000	19112
	Cv	0.037	0.128	0.135	0.073	0.080	0.100	0.316	0.193	0.416
	Illumination(%)	97.71	90.29	89.38	92.20	92.94	90.50	69.21	82.21	55.49
13:30	Average(Lux)	9021	6865	6417	7534	11112	32497	52424	53927	37280
	Variance	428	800	912	655	634	2331	1324	1066	1625
	Cv	0.047	0.117	0.142	0.087	0.057	0.072	0.025	0.020	0.044
	Illumination(%)	96.76	93.04	87.64	91.52	94.55	93.54	97.31	97.84	96.26
14:30	Average(Lux)	12096	8644	7912	8880	11863	27015	51228	53309	43105
	Variance	832	899	653	684	623	1454	3546	4118	3685
	Cv	0.069	0.104	0.083	0.077	0.053	0.054	0.069	0.077	0.085
	Illumination(%)	92.34	90.60	93.81	95.33	94.91	95.22	94.57	95.50	91.58

In Table 6, the illumination uniformity of 2mm thick glass as the light transmitting module from point A to point I and from 10:30 to 14:30 increased with the increase of time, the variation coefficient decreased slightly with the increase of time, the rest of the points increased with time, the variance except for point A increased slightly with time, the variance decreased slightly with the increase of time, the variance except for point A increased slightly with time, and decreased with the increase of time, the average point A, point F, point G, point H increased with the increase of time, and point B, point C, point D, point E, and point I decreased with the increase of time.

Table 6. Light uniformity and variation coefficient of 2mm thick glass transmittance component.

Time	2mm glass	A	B	C	D	E	F	G	H	I
10:30	Average(Lux)	9902	9074	8832	9122	10991	14192	52549	54144	52454
	Variance	628	5010	5686	5235	4189	2291	29768	32019	31339
	Cv	0.063	0.522	0.644	0.574	0.381	0.161	0.566	0.591	0.597
	Illumination(%)	93.99	65.98	59.89	62.86	75.45	90.64	34.62	31.72	31.01
11:30	Average(Lux)	9456	8788	9121	10278	13611	53302	59227	73413	36486
	Variance	1367	2964	3416	2708	346	33545	29411	5037	23825
	Cv	0.145	0.337	0.375	0.263	0.025	0.629	0.497	0.069	0.653
	Illumination(%)	91.16	78.5	76.51	84.28	97.50	28.08	42.81	93.06	48.73
12:30	Average(Lux)	9793	7747	7734	8933	12144	65639	75127	75470	41387
	Variance	434	400	791	405	441	2096	6677	13279	21467
	Cv	0.044	0.052	0.102	0.045	0.036	0.032	0.089	0.176	0.519
	Illumination(%)	94.97	96.91	92.75	97.03	95.86	96.79	90.76	83.68	40.41
13:30	Average(Lux)	9494	7467	7027	7905	11045	41105	67277	70382	57833
	Variance	300	663	586	210	326	21427	8882	7255	10947
	Cv	0.032	0.089	0.083	0.027	0.030	0.521	0.132	0.103	0.189
	Illumination(%)	96.94	93.44	94.97	96.99	96.60	42.86	85.33	88.23	78.97
14:30	Average(Lux)	11773	8288	7283	8085	10378	14806	53669	55271	50436
	Variance	667	651	561	562	707	915	4657	3782	2368
	Cv	0.057	0.079	0.077	0.070	0.068	0.062	0.087	0.068	0.047
	Illumination(%)	94.77	91.89	91.11	92.19	93.22	95.10	91.45	92.38	96.20

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 26 December 2023 doi:10.20944/preprints202312.1932.v1

In Table 7, the illumination uniformity of the 3mm thick glass translucent module from point A to point I and from 10:30 to 14:30 decreased with the increase of time, the variation coefficient increased with the increase of time, the variance increased with the increase of time, the average points A, B, C, D, E, and F increased with the increase of time, and the average points G, H and I decreased with the increase of time.

Table 7. Light uniformity and variation coefficient of 3mm thick glass transmittance component.

Time	3mm glass	A	B	C	D	E	F	G	H	I
10:30	Average(Lux)	8165	5556	5200	5998	8404	12613	69234	71640	65709
	Variance	439	380	397	463	110	643	4043	2468	510
	Cv	0.054	0.068	0.076	0.077	0.013	0.051	0.058	0.034	0.008
	Illumination(%)	93.93	96.01	94.71	93.46	99.10	95.32	93.36	96.47	99.40
11:30	Average(Lux)	7820	6548	6691	8200	12278	69336	70410	71778	21230
	Variance	473	527	222	491	1446	4832	299	3039	4317
	Cv	0.060	0.0800	0.033	0.060	0.118	0.070	0.004	0.042	0.203
	Illumination(%)	94.76	90.96	96.24	93.52	93.10	93.04	99.52	96.29	83.32
12:30	Average(Lux)	10639	9223	9104	10371	12292	47526	52557	56379	48093
	Variance	1032	2777	2676	2827	727	28626	33213	34108	26582
	Cv	0.097	0.301	0.294	0.273	0.059	0.602	0.609	0.605	0.553
	Illumination(%)	94.15	81.45	82.24	83.67	93.61	33.56	33.61	33.59	36.9
13:30	Average(Lux)	10511	8768	81.2	9220	11238	20650	50111	51299	48239
	Variance	1093	3339	3201	3593	1783	6321	27683	28179	27861
	Cv	0.104	0.381	0.393	0.390	0.159	0.306	0.552	0.549	0.566
	Illumination(%)	91.42	76.30	76.20	76.97	89.80	77.44	36.36	37.09	35.00
14:30	Average(Lux)	17584	22986	19327	22834	23440	27171	50479	42862	55392
	Variance	9495	24502	18756	22999	19510	19982	6235	20472	1599
	Cv	0.540	1.066	0.970	1.007	0.832	0.735	0.124	0.478	0.092
	Illumination(%)	68.53	38.23	42.01	39.32	48.24	55.98	87.98	44.88	96.68

5. Discussion

1. The use of grating plate as the light transmitting module can improve the light uniformity of the light and dark zone junction area in the low light area caused by the shading of photovoltaic modules in the zigzag photovoltaic greenhouse. However, the light transmittance of the grating plate is lower than that of the translucent glass, and the light entering through the translucent roof will be reduced, causing a low utilization rate of sunlight and lower light intensity under the grating plate in the greenhouse compared with ordinary translucent glass. From the perspective of light distribution characteristics, the grating plate has a high scattering feature to refract the light to an area larger than its own size, which improves the light intensity of some dark band areas, and the increased intensity would decrease with distance. Therefore, grating plates are a good way to deal with the need to block a part of the light and increase the light intensity near the band area. At the same time, it provides ideas for improving the light environment in the greenhouse by using the optical path of light transmitting materials to light.

2. In addition to this experiment, the greenhouse model that can change the inclination angle of the roof can also be used to determine the lighting environment in the greenhouse under different roof coverage rates. Since the model greenhouse is based on the size of the actual greenhouse and is scaled down, the light intensity in the room is affected by the skeleton. At the same time, due to the volume of the measuring instrument, the existing model fails to measure the light intensity in the greenhouse from different heights.

6. Conclusions

In this study, on the basis of constructing a zigzag photovoltaic greenhouse model, the light intensity of the model greenhouse under different roof inclination angles and different simulated solar altitude angles was compared through pre-experiments using grating panels and ordinary glass as light-transmitting modules, and the optimal roof inclination angle range suitable for field experiments was obtained. On this basis, the illumination intensity of the model greenhouse was measured when the grating plate and ordinary glass were used as the light transmitting components in different time periods of the day, and the illuminance of each measurement point was obtained and compared [25]. The following main conclusions were obtained:

(1) In the outdoor experiment, the roof inclination angle of the model greenhouse is 12 degrees, and the roof coverage rate is 41.92%. From the experimental results, it is not difficult to see that the light in the greenhouse with the light transmitting component is ordinary glass, the dark band is concentrated in the front end (A, B, C points) area, the bright band is concentrated in the rear end (G, H, I points) area, and the middle (D, E, F points) area belongs to the light and dark junction zone. At noon, when the grating plate is used as the light transmitting component, the uniformity of the points (A to I) in the north-south direction is the same as in the east-west direction. The light intensity in the front area of the greenhouse is the same as that of the grating group and the glass group. The grating plate can be used as the light transmitting module to reduce the light intensity of the bright belt, improve the light intensity at the intersection of light and dark, and expand the planting area in the photovoltaic greenhouse.

(2) When the grating plate is used as the light transmitting module, the light intensity from point G to point I in the greenhouse is greater than 20000Lx, and the light environment in other areas is less than 20000lx and greater than 5000Lx, which is suitable for planting shade-loving crops, and the light intensity of the 40-line specification with a thickness of 2mm can be maximized to improve the light intensity of the greenhouse. At present, the cost of grating plate on the market is about 90-120 yuan per square meter, which is roughly the same as the cost of glass, and there is the possibility of actual production.

In summary, grating panels can be used as greenhouse covering materials to improve the light intensity at the intersection of light and dark bands in photovoltaic greenhouses.

Author Contributions: Conceptualization, J.L.; methodology, B.W.; software, Y.S.; validation, Y.S.; formal analysis, B.W.; investigation, Y.S.; resources, B.W.; data curation,B.W.; writing—original draft preparation, Y.S.;

writing—review and editing, B.W.; visualization, Y.S.; project administration, J.L.; funding acquisition, J.L. All authors have read and agreed to the published version of the manuscript.

Funding: This research was supported by China Huaneng Group Co., Ltd. Headquarters Technology Project , grant number HNKJ22-HF77;Hainan Provincial Natural Science Foundation of China, grant number 322RC583..

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: All data are presented in this article in the form of figures and tables.

Acknowledgments: We would like to thank the Innovation and utilization team of tropical melon crop genetic germplasm, Hainan University.

Conflicts of Interest: The authors declare no conflict of interest.

Nomenclature

U_0	Illumination uniformity
Emin	Minimum illumination value
Eav	Average illuminance value

References

1. ZHOU C. Dr. Zhou inspected and visited the greenhouse facilities at the Arava scientific research base in Israel, Agricultural engineering Technology, 2016,36 (31): 65-68
2. Karpenko O .Optical Transmission Scanning and Hybrid Acousto-Optical Techniques for NDE and SHM of Structural Composites.Michigan State University. 2018.
3. Singh R,;Gite L. Technological Change in Paddy Production: A Comparative Analysis of Traditional and Direct Seeding Methods of Cultivation. AMA-Agricultural Mechanization in Asia Africa and Latin America, 2012, 43,3, 41-46.
4. Liu C,;Yang H,;Lai M. Evaluation of ecological compensation standards for county photovoltaic poverty alleviation in the context of agricultural modernization. Journal of Agricultural engineering, 2020,36 (16): 300-309
5. Semple L,;Carriveau R,;Ting S K.Assessing heating and cooling demands of closed greenhouse systems in a cold climate.International Journal of Energy Research, 2017. https://doi.org/10.1002/er.3752.
6. Boong-Joo,Lee.The Illumination Simulation in the Greenhouse using Daylight and Artificial Light for Energy Saving.The transactions of The Korean Institute of Electrical Engineers, 2017, 66(9):1359-1363. https://doi.org/10.5370/KIEE.2017.66.9.1359.
7. Liu J. A sawtooth shaped multi-span photovoltaic agricultural planting greenhouse: CN201320738494.4.2023.08.22
8. Liu J,;Wang B,;Sun F,;Chen Y,;Wu Xuyong. Practice and innovation of structural design of multi-building photovoltaic vegetable greenhouse in hot zone[J].Agricultural Engineering Technology, 2022, 42(16):22-29.
9. Li J,;Zuo S,; Wu F.The Tianlai Cylinder Pathfinder array: System functions and basic performance analysis. Chinese Science: Physics, Mechanics, Astronomy English Edition, 2020, 63(12):27. https://doi.org/10.1007/s11433-020-1594-8.
10. Zou Z ,; Shao X.*Environmental Engineering in Facility Agriculture*, China Agriculture Press, Beijing,2006, p. 19
11. Seifert E .OriginPro9.1: Scientific Data Analysis and GraphingSoftware Software Review.Journal of Chemical Information and Modeling, 2014, 54(5):1552-1552.
12. Li H,;Ji D,;Hu X.Comprehensive evaluation of combining CFD simulation and entropy weight to predict natural ventilation strategy in a sliding cover solar greenhouse. International Journal Of Agricultural And Biological Engineering, 2021(006):014.
13. Zhang J,;Shen K,;Chen D. Analysis of spatiotemporal changes in canopy characteristic temperature of solar greenhouses based on the Internet of Things. Journal of Agricultural Machinery, 2021,52 (07): 335-342
14. Choab N ,;Allouhi A,;El Maakoul A.Review on greenhouse microclimate and application: Design parameters, thermal modeling and simulation, climate controlling technologies.Solar Energy, 2019, 191(Oct.):109-137. https://doi.org/10.1016/j.solener.2019.08.042.

 doi:10.20944/preprints202312.1932.v1

15. Bulik,T,;Piacentini.Selection of astrophysical/astronomical/solar sites at the Argentina East Andes range taking into account atmospheric components.Advances in Space Research the Official Journal of the Committee on Space Research, 2016.
16. Igoe,D,;Turner.Characterization of cloud cover with a smart phone camera.Instrumentation science & technology: Designs and applications for chemistry, biotechnology, and environmental science, 2016, 44(1):23-34.
17. Ayet A ,;Tandeo P.Nowcasting solar irradiance using an analog method and geostationary satellite images.Solar Energy, 2018, 164(APR.):301-315. https://doi.org/10.1016/j.solener.2018.02.068.
18. Zhou Bo,; Sun W,; Guo Wl. Analysis of the impact of the gutter structure of a multi-span glass greenhouse on the light environment in cultivation areas . Journal of Agricultural Machinery, 2021,52 (05): 286-292
19. Giovannini L,; Goia F,;Lo V.A Comparative Analysis of the Visual Comfort Performance between a PCM Glazing and a Conventional Selective Double Glazed Unit.Sustainability, 2018, 10(10). https://doi.org/10.3390/su10103579.
20. Xu M,; Bu X,;Yu J.Compensation method of cloud infrared radiation interference based on a spinning projectile's attitude measurement.Journal of Applied Remote Sensing, 2018, 12(1):1. https://doi.org/10.1117/1.JRS.12.016031.
21. Lindh U,;Jgerbrand A K.Perceived Lighting Uniformity on Pedestrian Roads: From an Architectural Perspective.Energies, 2021. https://doi.org/10.3390/en14123647.
22. Hoda R,;Socio-Technical Grounded Theory for Software Engineering. 2021. https://doi.org/10.1109/ICSE-Companion52605.2021.00139.
23. Li X ,;Lu Z,;Zhou Q.A Cloud Detection Algorithm with Reduction of Sunlight Interference in Ground-Based Sky Images.Atmosphere, 2019(11). https://doi.org/10.3390/ATMOS10110640.
24. Yang Y,;Chen Z,; Xu T.Comparing the uniformity of light glass fiber felt based on process improvement, microstructural forming mechanism and physical properties.SAGE PublicationsSage UK: London, England, 2019(17). https://doi.org/10.1177/0040517518813714.
25. Lopez-Cruz I,;,Efrén F,; Salazar-Moreno R.Development and analysis of dynamical mathematical models of greenhouse climate: A review. European Journal of Horticultural Science, 2018, 83(5):269-279. https://doi.org/10.17660/eJHS.2018/83.5.1.
26. Bubolz K,;Schenk H,; Hirsch T.Influence of spatiotemporally distributed irradiance data input on temperature evolution in parabolic trough solar field simulations. SolarPACES 2015, 13.-16. Okt. https://doi.org/10.1063/1.4949150.
27. Lhmus,M,Bowlan.Diffraction of ultrashort optical pulses from circularly symmetric binary phase gratings[J].Optics Letters, 2012, 37(7):1238-1240. https://doi.org/10.1364/OL.37.001238.
28. Sahin M,;Oguz Y,;Buyuktumturk F.ANN-based estimation of time-dependent energy loss in lighting systems[J].Energy & Buildings, 2016, 116(mar.):455-467. https://doi.org/10.1016/j.enbuild.2016.01.027.
29. Shaik S,;Bhardwaj M,;Agarwal S.Evaluation of Optical Transmissivity of Transparent Materials on the Performance of Solar Flat Plate Collectors[J].Journal of Solar Energy Engineering, 2021(5):143. https://doi.org/10.1115/1.4050214.