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Article

Experiment on the Uniformity of Internal Lighting in Zigzag Photovoltaic Greenhouses by Grating Plates

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Abstract: As one of the main projects of facility agriculture promotion, the PV (photovoltaic) greenhouse has the problems of PV 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 PV greenhouses. Altogether, 20 line/inch 3 mm and 30 line/inch 3 mm, 40 line/inch 2 mm, 25 line/inch 4 mm grating plates and 2 mm and 3 mm 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 ages easily with low light transmittance. It can also improve the use of land under the shade of PV modules to provide a better growth environment for crops. The test results show that using grating plates can maximize the light intensity of the greenhouse and solve the problem of uneven distribution of light inside the greenhouse caused by obstruction of PV equipment and greenhouse framework. In sunny weather, the light intensity in three rows of the measurement points at the north side in the greenhouse is greater than 20,000 Lx, and the light environment in other areas is between 5000 Lx and 20,000 Lx, which is suitable for planting shade-loving crops.

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

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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, and solar energy. Among them, solar energy is the most popular energy, and PV power generation is one of the main forms of solar energy utilization. PV power generation includes rooftop PV, water PV, and traditional PV ground power stations. A PV greenhouse is an application form of PV power generation, which is mainly used in agricultural production, especially in areas with limited land resources or a lacking power supply. A PV 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]. PV 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, a PV 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 PV 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. At present, the main covering material for solar greenhouses is plastic film, and the most commonly used greenhouse film can be divided into three types based on resin raw materials: PVC (polyvinyl chloride) film, PE (polyethylene) film, and EVA (ethylene vinyl acetate) film. The performance of these three types of greenhouse films is different. PVC greenhouse films have the best insulation effect and are easy to stick and repair but are prone to pollution and have a rapid decrease in transmittance; PE greenhouse film has good transparency and is easy to clean dust and dirt, but its insulation performance is poor. The insulation and light transmittance of EVA greenhouse film are between PE and PVC greenhouse films [2]. There are still some challenges in PV greenhouse technology, such as the cost, efficiency, and reliability of PV 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 PV greenhouses caused by the shading of PV 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 PV greenhouses can effectively improve the light intensity in the greenhouse [3,4]. Liu Chengyu et al. pointed out that a large number of experimental studies were carried out on PV greenhouses. The experimental results of these studies summarized the problems and opinions regarding the research and development of PV greenhouses, as well as the relatively low utilization rate of light energy and the high maintenance price of PV equipment. It is particularly important to ensure that the light uniformity in the PV greenhouse is suitable for plant growth and ensures the thermal insulation function of the greenhouse while not affecting the operation of PV power generation in the greenhouse [5,6].

In this study, grating panels with different thicknesses and numbers of lines were used as PV 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 [7,8]. 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.

2. Materials

2.1. Zigzag PV Greenhouse

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

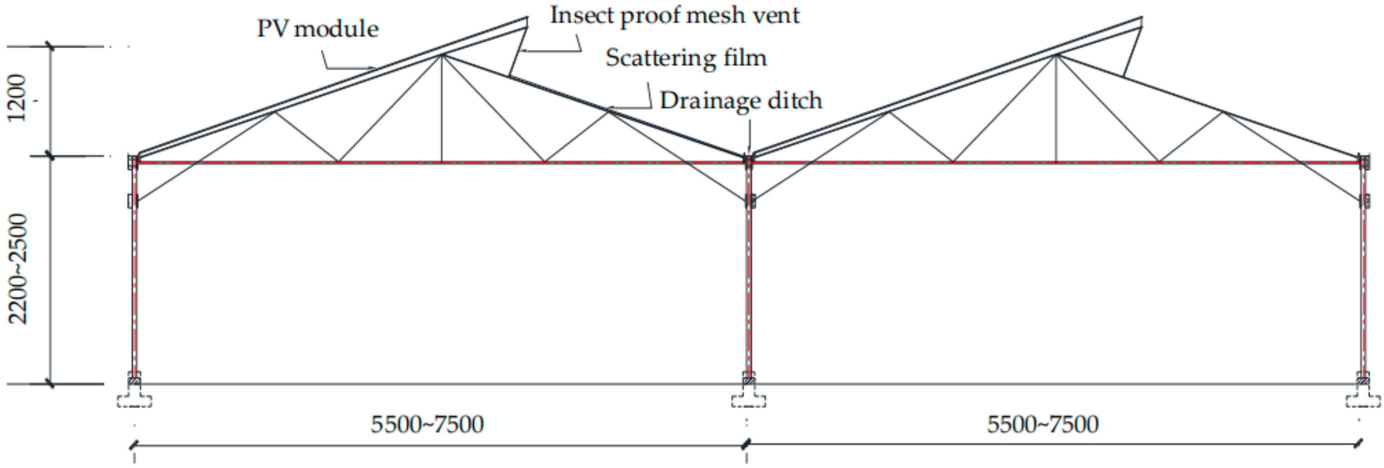

Figure 2. Schematic diagram of zigzag PV greenhouse structure (mm).

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 PV vegetable greenhouse reasonably optimizes the layout of the roof structure and uses PV 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 PV vegetable greenhouses [9].

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

The research on indoor lighting problems of zigzag PV 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 greenhouse. The problem of shading and lighting in greenhouses also needs to solve the problem of reasonable distribution of sunlight in crops and PV power generation and maximize the benefits of agriculture and PV industry.

2.2. Zigzag PV 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. Moreover, 20 mm $\times$ 20 mm 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 [10]. Figures 4–6 show 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. There are some slight differences between the model in the experiment and the actual PV greenhouse, but this experiment is to explore the selection of materials with different specifications of grating plates for the uniformity of internal lighting in the serrated PV greenhouse. (Simulate the sawtooth-shaped PV greenhouse skeleton model as European standard industrial aluminum profiles because this experiment used a sawtooth-shaped PV greenhouse simulated by Professor Liu's patent, and the PV panels used were nontransparent).

In order to simulate the problem of uneven distribution of illumination in the greenhouse caused by PV panel shading, we used black waterproof adhesive to simulate PV panels. Because the main focus of this study is on the impact of grating panels on the uniformity of illumination in the greenhouse, we mainly considered whether the shading is complete when simulating PV panels. Therefore, we chose to cover the lightweight wooden board with black tape for simulation.

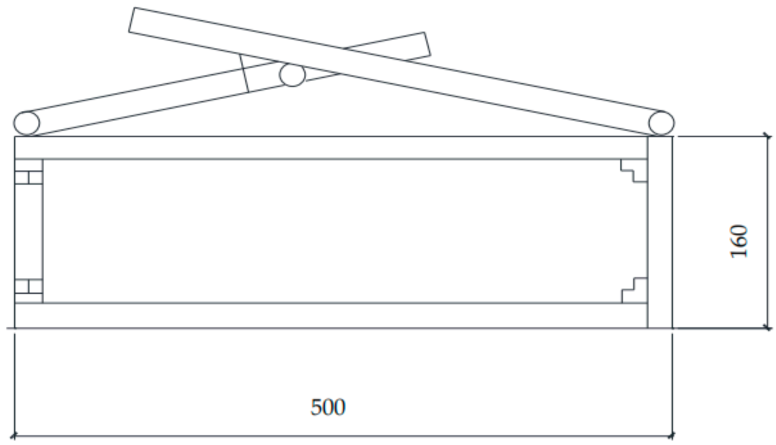

Figure 4. Schematic diagram of greenhouse model structure (mm).

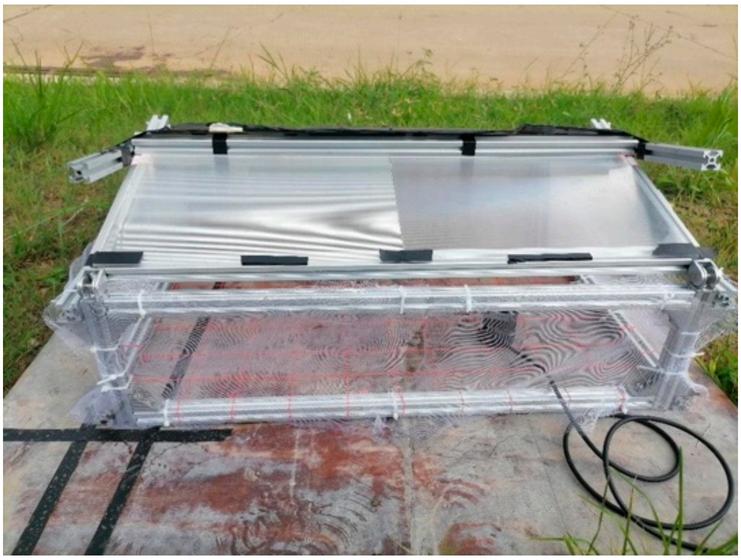

Figure 5. North end of the field experiment model (insect net can be opened).

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 distances of 5.5 cm, 14.50 cm, 23.50 cm, 32.50 cm, 41.50 cm, and 50.50 cm 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 3.0 cm, 8.0 cm, 13.0 cm, 18.0 cm, 23.0 cm, 28.0 cm, 33.0 cm, 38.0 cm, and 43.0 cm, which were recorded as point A to point I.

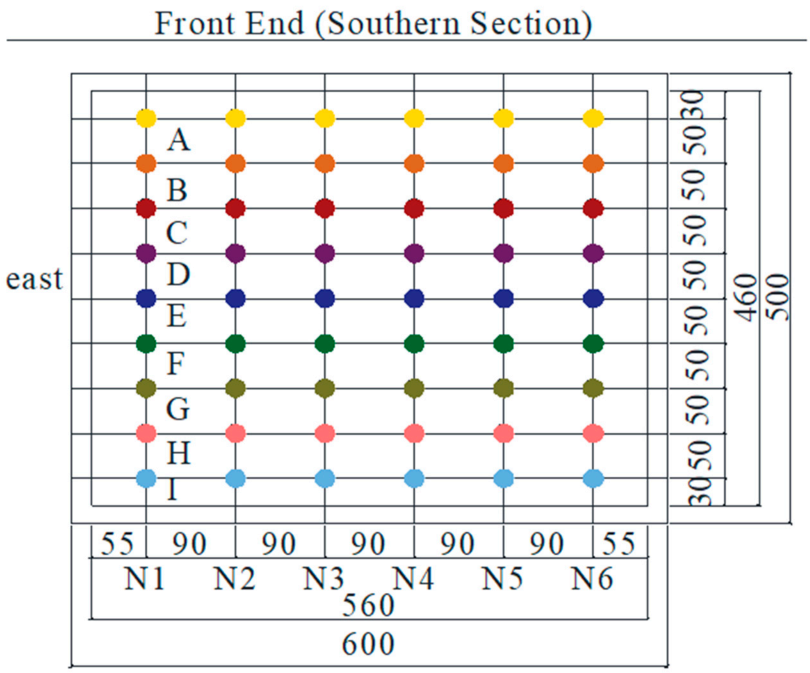

Figure 7. Schematic diagram of the front and back sections of the light intensity measurement point (mm).

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 1 June 2023 (sunny) and from 10:00 to 16:00 on 2 June (sunny).

Due to the fact that these two days are theoretically the period when Hainan Island is at its maximum solar altitude angle, the optimal experimental time range for selection is from June to July. Due to the fact that this experiment mainly discusses the influence of grating plates on the uniformity of indoor lighting in serrated PV cells, there is not much significance in selecting the appropriate time. The time required for readers to reproduce this experiment was also short, reflecting the repeatability of the experimental results.

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

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 [11], the number of inclination angles of the south roof $\beta > 90° - 40° - \alpha = 50° - \alpha$ (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 (the polymer of the grating plate is plastic) was tested one by one. Finally, Origin64 software was used for data analysis and comparison [12].

Table 1. Experimental arrangement.

Roof Inclination Angle/°	Point	Translucent Components	Data Acquisition (Time)
12	A	Translucent glass:	10:30
	B	2 mm glass	11:30
	C	3 mm glass	12:00
	D	Grating plate:	12:30
	E	20 line/inch 3 mm	13:30
	F	30 line/inch 3 mm	14:30
	G	25 line/inch 4 mm	
	H	40 line/inch 2 mm	
	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, 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. [13], the relevant lighting characteristics were analyzed by the one-day variation law and the significance Duncan analysis was performed on this basis.

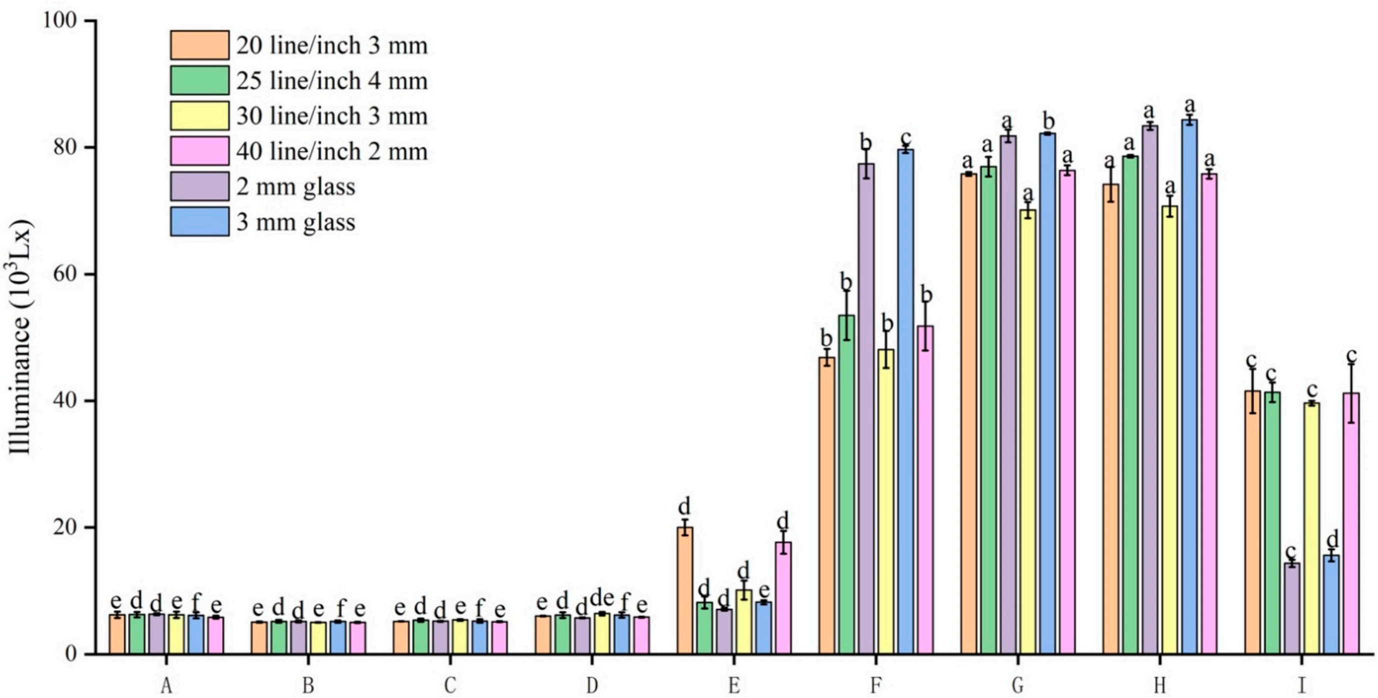

Figure 8. At 12:00 a.m. The light distribution of each point in the north–south direction of the corresponding area in each plate greenhouse. (Where there is a single marked letter, the difference is not significant, and where there are different marked letters, the difference is significant).

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 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 the glass at point F is greater than that of the 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 [14].

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. [15] Bulik, T, Piacentini et al. [16] 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. [17], and Ayet A et al. [18], 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 [19].

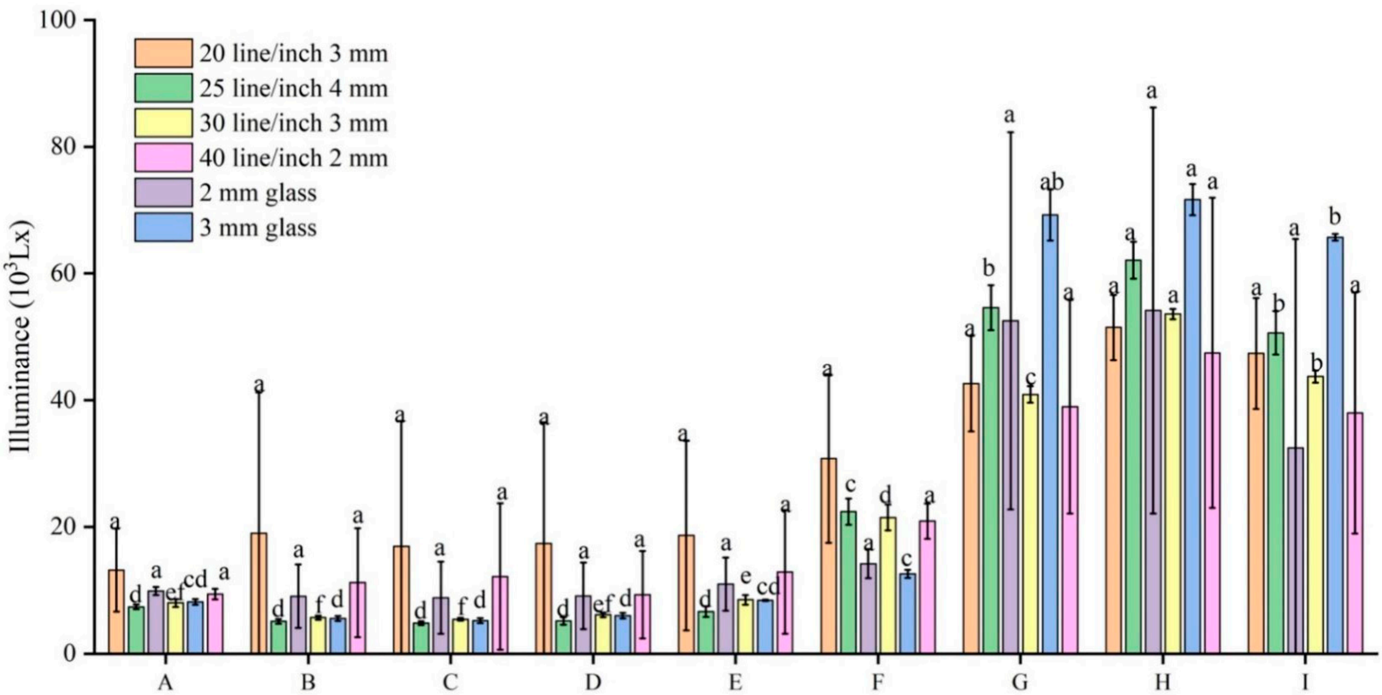

Figure 9. At 10:30 a.m. Average light intensity at each point. (Where there is a single marked letter, the difference is not significant, and where there are different marked letters, the difference is significant).

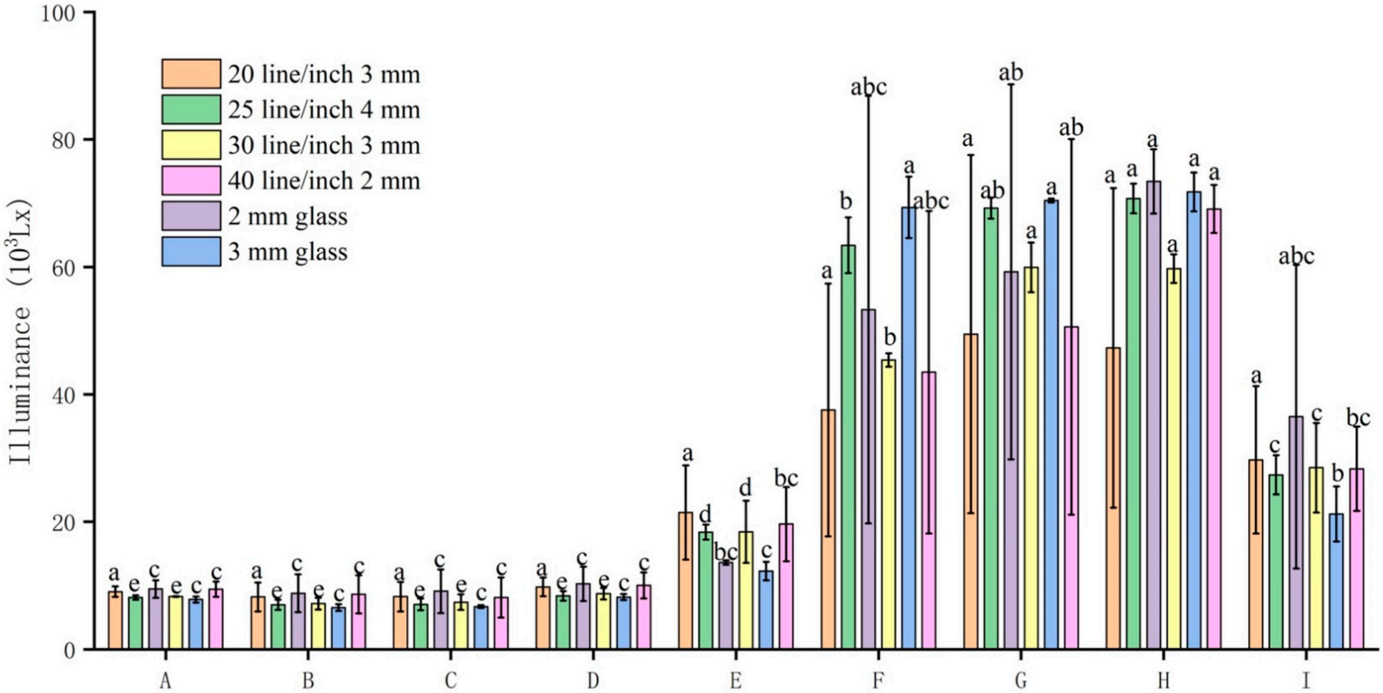

Figure 10. At 11:30 a.m. Average light intensity at each point. (Where there is a single marked letter, the difference is not significant, and where there are different marked letters, the difference is significant).

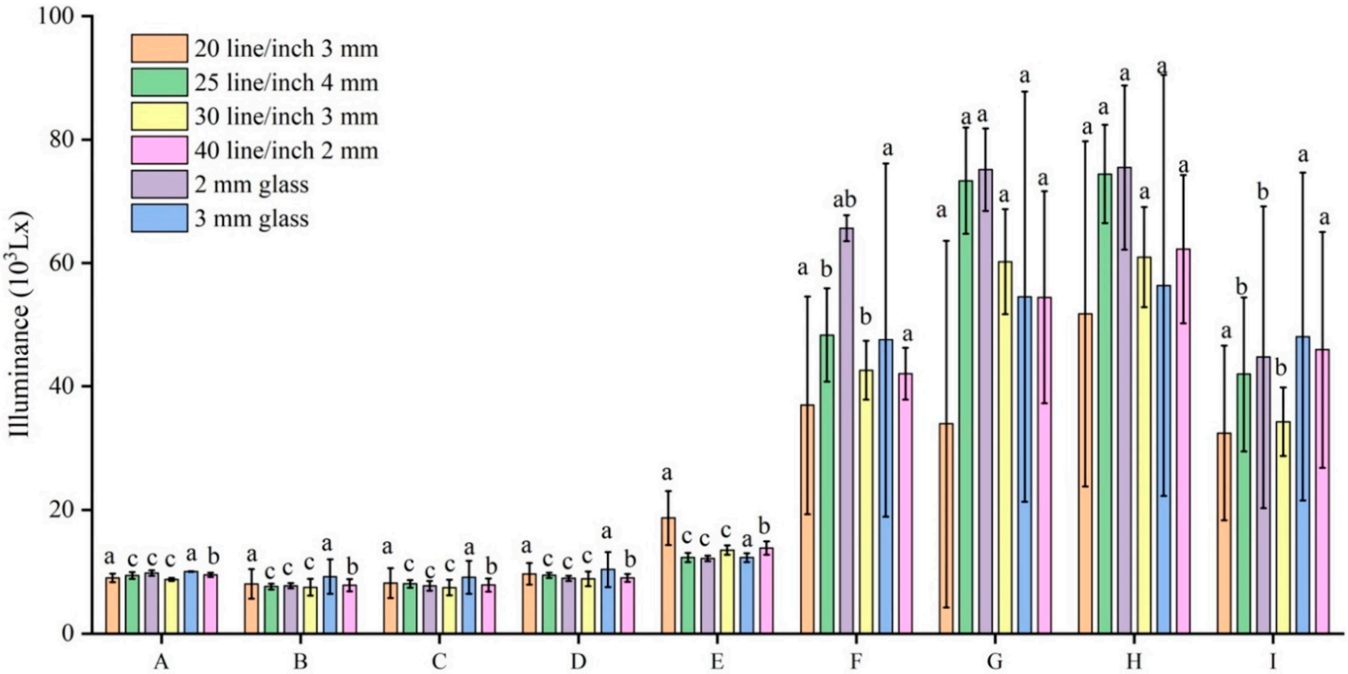

Figure 11. At 12:30 p.m. Average light intensity at each point. (Where there is a single marked letter, the difference is not significant, and where there are different marked letters, the difference is significant).

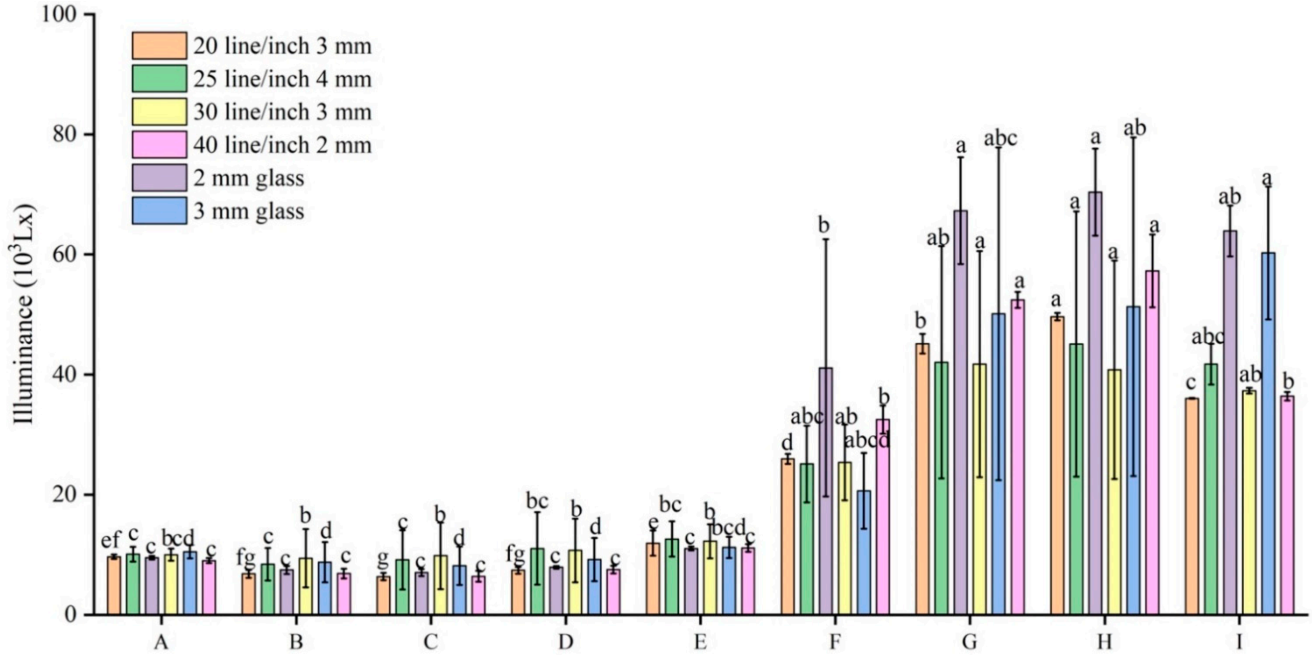

Figure 12. At 13:30. Average light intensity at each point. (Where there is a single marked letter, the difference is not significant, and where there are different marked letters, the difference is significant).

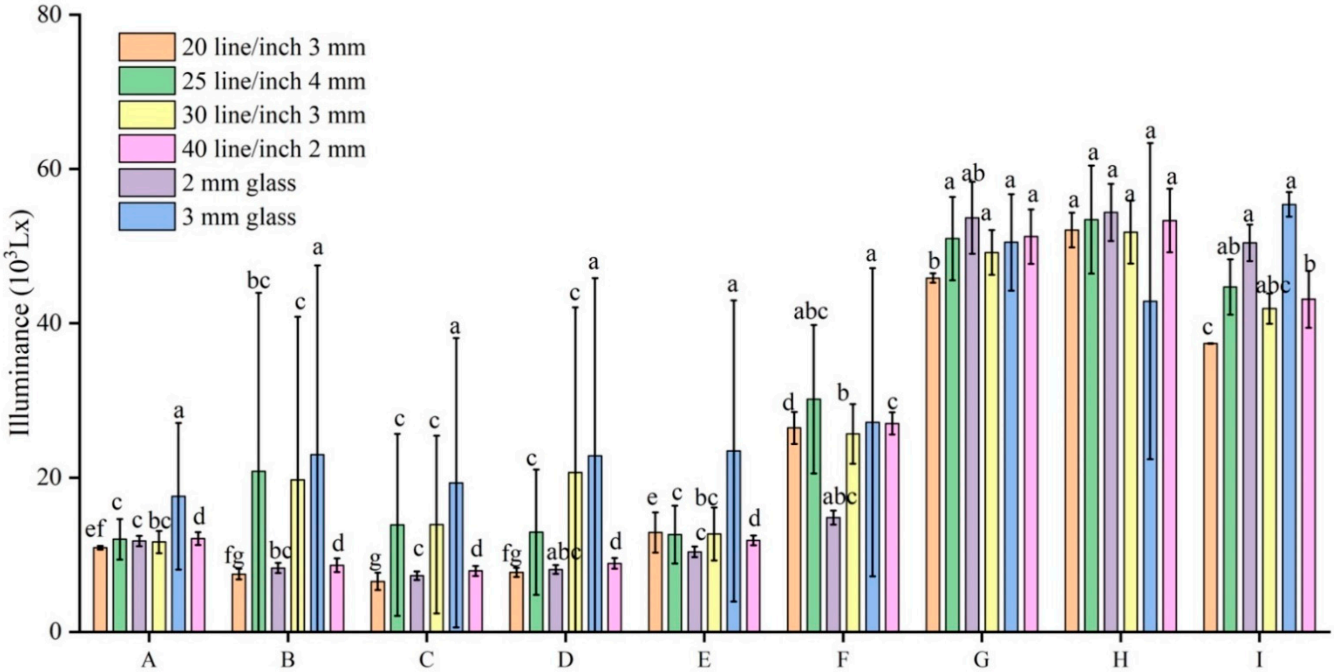

Figure 13. At 14:30. Average light intensity at each point. (Where there is a single marked letter, the difference is not significant, and where there are different marked letters, the difference is significant).

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 [19–22]. 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 [23]. In fact, the light intensity of the outdoors changes at any time [24], 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 is at noon, the blocking of water vapor will also affect the measurement results [25,26].

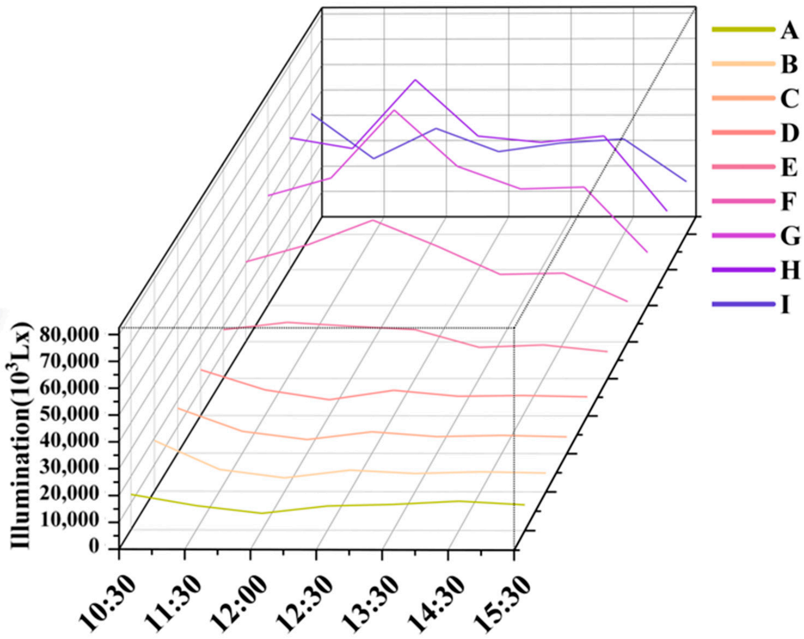

Figure 14. The average illumination intensity of each point of the 20 line/inch 3 mm thick grating plate at different times (illuminance at different time points from point A to point I).

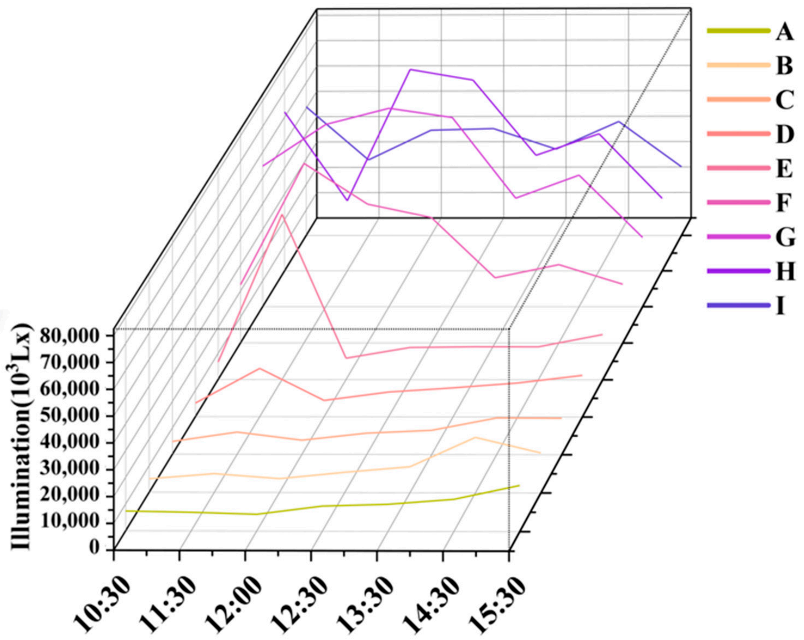

Figure 15. The average illumination intensity of each point of the 25 line/inch 4 mm thick grating plate at different times (illuminance at different time points from point A to point I).

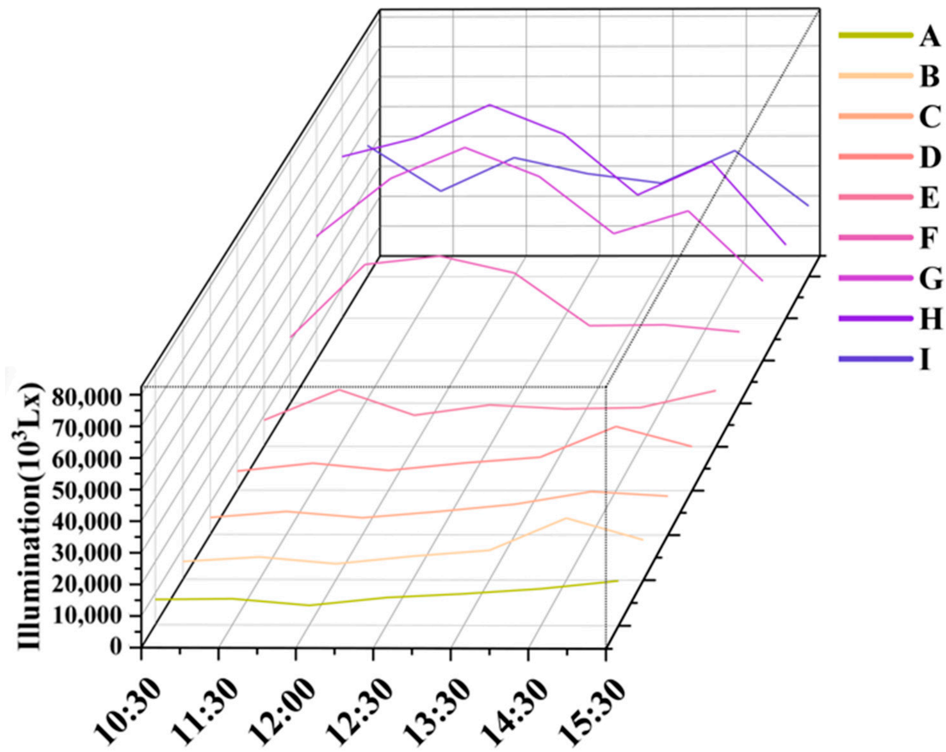

Figure 16. The average illumination intensity of each point of the 30 line/inch 3 mm thick grating plate at different times (illuminance at different time points from point A to point I).

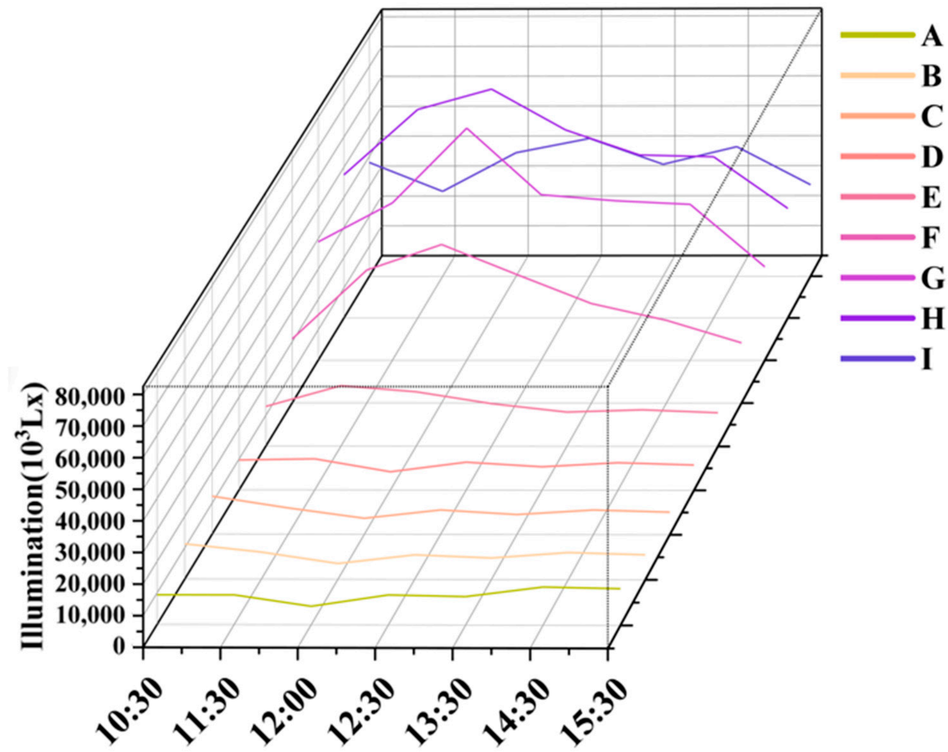

Figure 17. The average illumination intensity of each point of the 40 line/inch 2 mm thick grating plate at different times (illuminance at different time points from point A to point I).

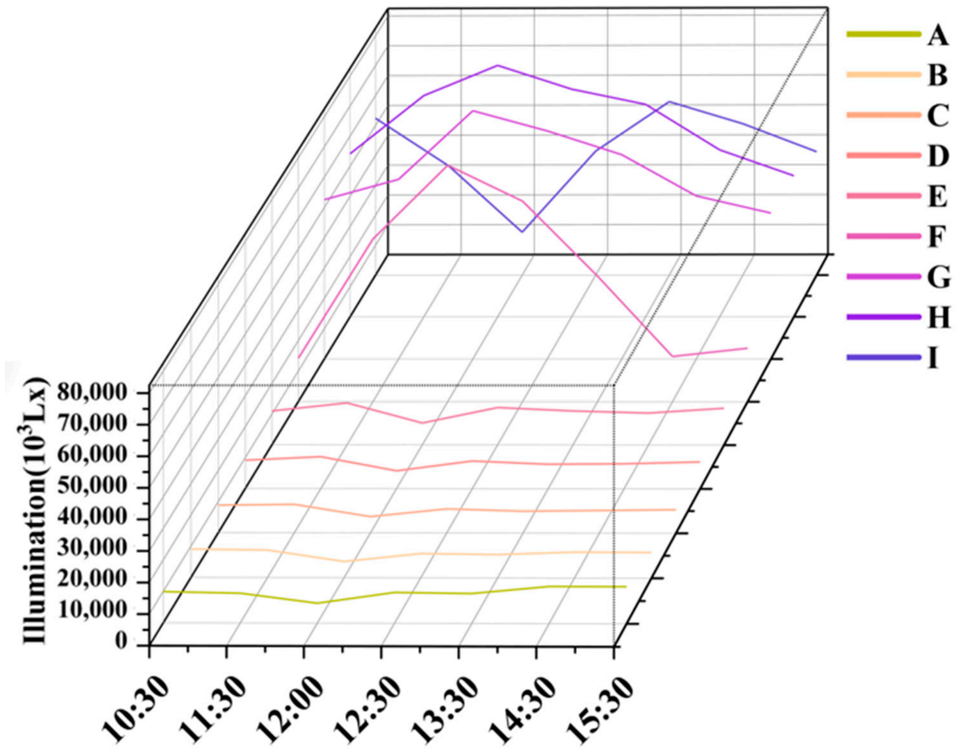

Figure 18. The average light intensity of each dot band of 2 mm thick glass at different times (illuminance at different time points from point A to point I).

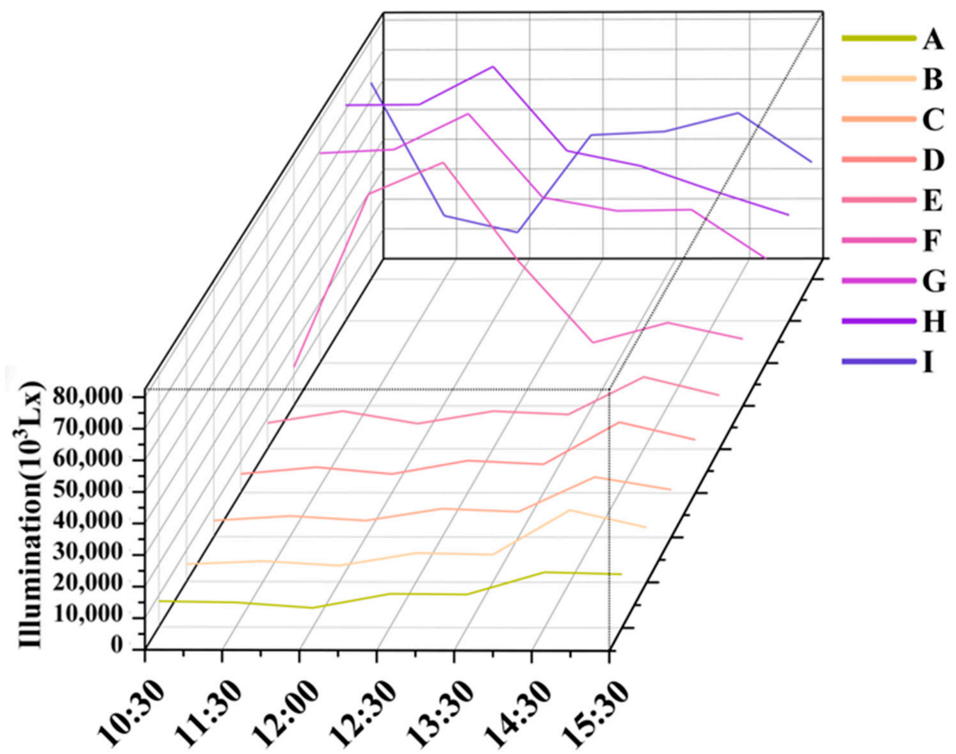

Figure 19. The average light intensity of each dot band of 3 mm thick glass at different times (illuminance at different time points from point A to point I).

4.3. Light Uniformity in the Greenhouse

Light Uniformity and Variation Coefficient

Tables 2–7 show the light uniformity and variation coefficient in the model greenhouse at different time periods 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. However, it is not difficult to see that the coefficient of variation of the illumination uniformity of the grating plate is relatively small, indicating that the illumination uniformity of the grating plate is superior to that of glass [27–30]. The results of data processing are as follows:

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

Time	20 Line/Inch 3 mm	A	B	C	D	E	F	G	H	I
10:30	Average (Lux)	13,204	19,023	16,967	17,407	18,648	30,788	42,619	51,477	47,391
	Variance	6540	22,226	19,731	19,084	14,952	13,310	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	21,463	37,555	49,452	43,701	29,714
	Variance	829	2293	2334	1469	7380	19,831	28,091	25,080	11,564
	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	18,696	36,957	53,929	52,073	32,435
	Variance	691	2395	2417	1724	4369	17,637	30,407	29,221	14,127
	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
13:30	Average (Lux)	9658	6819	6363	7419	11,937	25,959	45,146	46,941	35,807
	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)	10,925	7501	6888	7732	12,879	26,428	45,861	52,064	37,354
	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 3 mm 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 in time. The coefficient of variation of each point fluctuates little, and its own value is also very small, indicating a relatively stable change.

In Table 3, the illumination uniformity of the 25-line 4 mm 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 in time, the variation coefficient increased with the increase in time, the variance increased with the increase in time, the average point G, point H and point I decreased with the increase in time, and the other points increased with the increase in time. The coefficient of variation of each point fluctuates little, and its own value is also very small, indicating a relatively stable change.

In Table 4, the illumination uniformity of the 30-line 3 mm 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 in time, the variation coefficient increased with time, the variance increased with the increase in time, and the variance increased with the increase in time. The coefficient of variation of each point fluctuates little, and its own value is also very small, indicating a relatively stable change.

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

Time	25 Line/Inch 4 mm	A	B	C	D	E	F	G	H	I
10:30	Average (Lux)	7396	5065	4822	5164	6655	22,408	54,588	62,107	50,615
	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	18,387	63,385	69,224	70,738	27,373
	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	12,317	48,343	73,348	74,430	41,962
	Variance	540	468	615	412	755	7606	8581	7972	12,486
	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)	10,104	9750	9164	11,042	12,616	25,106	42,049	45,063	33,875
	Variance	1211	4999	4936	6048	2943	6374	19,338	22,079	13,807
	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)	12,001	20,822	13,874	12,921	12,601	30,164	50,966	53,427	44,685
	Variance	2623	23,121	11,788	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

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

Time	30 Line/Inch 3 mm	A	B	C	D	E	F	G	H	I
10:30	Average (Lux)	8011	5681	5429	6154	8516	21,483	40,911	53,604	43,729
	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	18,439	45,389	59,922	59,721	28,496
	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	13,514	42,574	60,516	60,966	34,265
	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)	10,004	9421	9822	10,729	12,250	25,349	41,733	40,815	31,104
	Variance	1007	4856	5564	5299	2827	6305	18,830	18,184	10,752
	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)	11,645	19,694	13,903	20,654	12,680	25,656	41,968	51,813	41,898
	Variance	1454	21,146	11,520	21,417	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

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

Time	40 Line/Inch 2 mm	A	B	C	D	E	F	G	H	I
10:30	Average (Lux)	9405	11,212	12,172	9641	12,899	20,918	38,975	47,467	37,986
	Variance	845	8610	11,568	6609	9737	2795	16,851	24,483	19,033
	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	10,027	19,644	43,479	51,796	69,087	28,332
	Variance	1190	2989	2872	2065	5843	25,311	30,460	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
12:30	Average (Lux)	9503	7830	7856	9000	13,836	42,032	54,445	62,260	45,913
	Variance	348	1001	1058	655	1104	4201	17,210	12,000	19,112
	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	11,112	32,497	52,424	53,927	37,280
	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)	12,096	8644	7912	8880	11,863	27,015	51,228	53,309	43,105
	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

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

Time	2 mm Glass	A	B	C	D	E	F	G	H	I
10:30	Average (Lux)	9902	9074	8832	9122	10,991	14,192	52,549	54,144	52,454
	Variance	628	5010	5686	5235	4189	2291	29,768	32,019	31,339
	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	10,278	13,611	53,302	59,227	73,413	36,486
	Variance	1367	2964	3416	2708	346	33,545	29,411	5037	23,825
	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	12,144	65,639	75,127	75,470	41,387
	Variance	434	400	791	405	441	2096	6677	13,279	21,467
	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	11,045	41,105	67,277	70,382	57,833
	Variance	300	663	586	210	326	21,427	8882	7255	10,947
	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)	11,773	8288	7283	8085	10,378	14,806	53,669	55,271	50,436
	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

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

Time	3 mm Glass	A	B	C	D	E	F	G	H	I
10:30	Average (Lux)	8165	5556	5200	5998	8404	12,613	69,234	71,640	65,709
	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	12,278	69,336	70,410	71,778	21,230
	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)	10,639	9223	9104	10,371	12,292	47,526	52,557	56,379	48,093
	Variance	1032	2777	2676	2827	727	28,626	33,213	34,108	26,582
	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)	10,511	8768	81.2	9220	11,238	20,650	50,111	51,299	48,239
	Variance	1093	3339	3201	3593	1783	6321	27,683	28,179	27,861
	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)	17,584	22,986	19,327	22,834	23,440	27,171	50,479	42,862	55,392
	Variance	9495	24,502	18,756	22,999	19,510	19,982	6235	20,472	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

In Table 5, the illumination uniformity of the 40-line 2 mm 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 in time, and the variance decreased with the increase in time. The coefficient of variation of each point fluctuates little, and its own value is also very small, indicating a relatively stable change.

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

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

5. Discussion

1. The use of a 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 PV modules in the zigzag PV 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. The model of the measuring instrument illuminometer is TES-1330A.

6. Conclusions

This study is based on the construction of a zigzag PV greenhouse model, using grating panels and ordinary glass as light-transmitting modules. 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. 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 PV 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 20,000 Lx, and the light environment in other areas is less than 20,000 lx and greater than 5000 Lx, which is suitable for planting shade-loving crops, and the light intensity of the 40-line specification with a thickness of 2 mm can be maximized to improve the light intensity of the greenhouse. At present, the cost of grating plates on the market is about 90–120 CNY per square meter, which is roughly the same as the cost of glass, and there is the possibility of actual production. Why is this specification of grating most suitable for improving indoor lighting? It may be because the diffraction effect brought on by the grating itself leads to an increase in indoor lighting, which is very interesting.

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

7. Patents

One patent has been applied in China in this manuscript (Patent No. CN201320738494.4)

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Nomenclature

U_0	Illumination uniformity
E_{min}	Minimum illumination value
E_{av}	Average illuminance value

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