

Article

Comparison of Ray Tracing Software Performance Based on Light Intensity for Spinach Growth

Chengyao Jiang ^{1,†}, Kexin Zhang ^{1,†}, Yue Ma ^{2,†}, Yu Song ^{2,*}, Mengyao Li ¹, Yangxia Zheng ¹, Tonghua Pan ³ and Wei Lu ^{1,*}

¹ College of Horticulture, Sichuan Agricultural University, Chengdu 611130, China; catherinejiang@126.com (C.J.); zhangkexin0722@126.com (K.Z.); limy@sicau.edu.cn (M.L.); zhengyangxia@163.com (Y.Z.)

² Crop Research Institute, Xinjiang Academy of Agricultural Sciences, Urumqi 830091, China; my0988221@163.com

³ School of Agricultural Engineering, Jiangsu University, Zhenjiang 212013, China; panthujs12345@ujs.edu.cn

* Correspondence: songyu150@163.com (Y.S.); luwei-1213@163.com (W.L.)

† These authors contributed equally to this work.

Abstract

With the development of modern agricultural technology, plant factories have become an important way to achieve efficient and sustainable crop production. Accurate understanding of the light received by plants is the key to improving the light energy utilization efficiency of lamps and ensuring the benefits of plant factories. Ray tracing technology, as one of the key technologies in plant factories, is of great significance to analyze the growing light environment of vegetables. Spinach has high nutritional value and is loved by the public and is one of the main crops grown in plant factories. In this paper, LightTools, TracePro, and Ansys Lumerical FDTD Solution, which are currently mature light environment tracking software in the field of lighting, are selected as the research objects to investigate their performance in simulating the light environment of spinach leaf surfaces under different planting arrangements and different lamp source distances. The results show as follows: Under the rectangular planting arrangement, the leaves received more light, and the plants grew faster. Different planting arrangements of plants had little effect on the simulation effect of the same kind of software, but the simulation effect of the three kinds of software under the same planting arrangement was significantly different, and the difference between the simulated value and the measured value of TracePro was the least. Further, TracePro was used to trace and simulate the leaf surface light conditions of spinach under a rectangular planting arrangement at different lighting distances, and the simulation results showed that there was no significant difference between the software simulation value and the measured value, and the simulation accuracy was the highest when the distance from the light source was 30 cm. Therefore, TracePro software can accurately simulate the light intensity of spinach leaves during the growth process and is most suitable for monitoring the change of light environment of spinach growth in plant factories.

Keywords: plant factories; ray tracing software; spinach; software comparison



Academic Editors: Inkyu Kang, Jingi Yoo and Nay Myo Win

Received: 22 July 2025

Revised: 26 August 2025

Accepted: 27 August 2025

Published: 30 August 2025

Citation: Jiang, C.; Zhang, K.; Ma, Y.; Song, Y.; Li, M.; Zheng, Y.; Pan, T.; Lu, W. Comparison of Ray Tracing Software Performance Based on Light Intensity for Spinach Growth. *Agriculture* **2025**, *15*, 1852. <https://doi.org/10.3390/agriculture15171852>

Copyright: © 2025 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).

1. Introduction

Spinacia oleracea L., an annual or biennial herbaceous green leafy vegetable belonging to the genus *Spinacia* in the family *Amaranthaceae*, is an important vegetable crop [1]. In

2016, China became the world's largest producer and consumer of spinach [2]. Spinach has a sweet and tender taste and is rich in nutritional value, containing high levels of protein, various vitamins, inorganic salts, etc. Among them, the vitamin A content in spinach is comparable to that in carrots [3]. Spinach has shown a wide range of beneficial effects on human health, such as lowering blood sugar and blood lipids [3].

During the growth of spinach, its surrounding environment, such as light, air, water, temperature, etc., will affect its growth, among which light is one of the important factors affecting the growth and development of spinach. Previous studies have respectively shown that different light conditions have significant impacts on the germination rate and growth and development of spinach seeds [4–6]. Therefore, when cultivating spinach in plant factories, the growth cycle of spinach can be regulated by changing the light duration and light intensity irradiated on spinach [5–7], so as to realize the year-round supply or off-season marketing of spinach. In plant factories, light-emitting diodes (LEDs) are often used as artificial light sources. This material was invented in the 1960s [8], and with the development of technology, LEDs are now widely used in various fields. LED light sources have the advantages of high photoelectric conversion efficiency, small size, long service life, and low energy consumption [9–11], so they have become the most commonly used light source materials in modern agricultural production [12]. In particular, the use of LED light sources allows precise control of the light spectrum, and they can be automatically controlled, with energy-saving and high efficiency, making them the best choice for the light environment of plant growth in plant factories [13–15]. However, for plants, as the change in canopy morphology during the growth process accentuates the unevenness of the light distribution received by the leaf surface, the middle and lower leaves are often in a shaded state. Even when the upper leaves have reached light saturation, the middle and lower leaves still fail to meet the optimal light conditions. This structural light deficiency is particularly prominent in traditional array-type LED light source systems, leading to a difference in the growth rate of plants in the same batch of more than 30% and seriously restricting the yield per unit area [5–7]. Therefore, how to optimize the LED array form and adopt innovative cultivation layouts has become a research hotspot in the efficient production of plant factories in recent years.

With the development of modern agricultural production, digital plant technology [16–18], which digitizes plants through computer technology to realize the perception and understanding of the behaviors of plant life systems and agricultural production systems [18], has gradually been widely applied in the intelligent production monitoring of horticultural crops. These technologies are also driving continuous innovation in the field of LED plant lighting [19–26]. Through light tracing and tracking in digital plant technology, a spinach model can be created in optical simulation software, and then the light conditions on various plant leaves can be analyzed using the light tracing function in the corresponding software. Ray tracing technology, also known as light tracing, is a general technology derived from geometric optics that obtains the model of the light path by tracking the light rays interacting with optical surfaces. With the continuous development of computer graphics processing technology, ray tracing technology has gradually received hardware-level support. In this experiment, three simulation software, namely Light Tools, TracePro, and Ansys Lumerical FDTD Solution, were selected to track and analyze the light on spinach leaves. LightTools is an optical system modeling software developed by Optical Research Associates (ORA) in the United States in 1995, and it is equipped with an illumination template supporting the main program, which solves the problem of computer-aided design for lighting systems [24]. The software is characterized by high flexibility in lighting systems with various light sources and observation angles [25,26]. TracePro is a set of optical simula-

tion software commonly used in lighting systems, optical analysis, radiometric analysis, and photometric analysis [27–29]. This software has the characteristics of an intuitive interface, simple operation, and low time consumption. Ansys Lumerical FDTD Solution is simulation software based on the solution of Maxwell's equations, with an intuitive interface, powerful simulation functions, and good visual performance, which is often used in scenarios requiring three-dimensional analysis of data [30]. However, so far, the application of these three ray-tracing software in the field of plant lighting, especially in the intelligent production of horticultural crops relying on plant factories, has rarely been involved.

The purpose of this study is to fully understand the distribution of light intensity on spinach leaves in plant factories, use three relatively advanced existing light simulation software programs, namely LightTools, TracePro, and Ansys Lumerical FDTD Solution, for modeling and analysis, and investigate their performance in simulating the light environment on spinach leaves under different planting arrangements and different light source distances from the aspects of operating environment, modeling process, and reliability comparison. It aims to screen reliable, intuitive, and effective light environment monitoring and analysis software for spinach growth so as to provide technical and theoretical references for improving the light energy utilization efficiency of plant factories and enhancing the benefits of spinach cultivation.

2. Materials and Methods

Mainly data cultivation and plant verification work of this study were conducted in Chengdu and Urumqi, China. And the whole experiment period lasted from 2024 autumn to 2025 spring.

2.1. Materials Preparation

2.1.1. Plant Materials

The spinach variety selected was 'Shengxia Xianfeng', which has a moderate growth rate and an upright plant type and is widely used in plant factory production. All plants were provided by the Vegetable Laboratory of Sichuan Agricultural University.

2.1.2. Light Condition Instruments

The LED lamp was designed by the Light Environment Innovation Group at Sichuan Agricultural University. The LED lamp for plant production was in a uniform size of 1.2 m in length, 1800 lm in luminous flux, and full spectrum. Each LED lamp bead was 2.8 mm in length, 3.5 mm in width, and 0.8 mm in thickness. It was with a power of 0.2 W and a luminous flux of 25 lm. So each LED unit contains 72 lamp beads ($1800/25 = 72$).

The illuminance sensor used in this study was RS485, produced by Jianda Renke, Hangzhou, with a measurement range of 0–130,000 lux and a measurement accuracy of $\pm 6\%$.

2.1.3. Light Tracing Software

Three kinds of professional and widely used light tracing software were used in this study: LightTools 8.6, TracePro 7.4.3, and Ansys Lumerical FDTD Solution 2024.

2.2. Test Methods

2.2.1. Arrangement of Spinach Cultivation and Determination of Leaf Illuminance

Spinach seeds were sown in seedling trays in a germination room with a temperature of 30 °C and relative humidity of 90% for 3 days [5]. Then, the plants were transported into a plant cultivation room with a light cycle of 16 h/8 h (day/night), a temperature of 28 °C/20 °C (day/night), and a relative humidity of $70 \pm 3\%$ [5]. When plants grew to a

stage with 2–3 true leaves, 64 seedlings with uniform growth were selected and divided into groups of 16. Four planting patterns, according to the results of the preliminary experiment, were set: equal difference (T1), rectangle (T2), hexagon (T3), and diamond (T4), as shown in Figure 1. A light substrate was used for seedling cultivation, with the substrate ratio of peat: vermiculite: decomposed organic fertilizer = 2:1:1. The experiment was conducted in the plant factory of Sichuan Agricultural University.

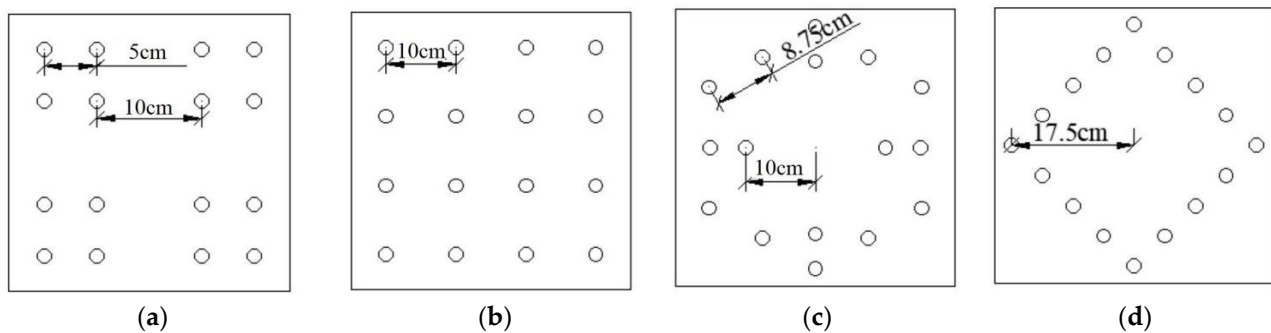


Figure 1. Spinach Cultivation Arrangement: (a) equal difference (T1), (b) rectangle (T2), (c) hexagon (T3), and (d) diamond (T4).

The illuminance on the spinach leaf surface was continuously measured using an illuminance sensor, and the average plant height of spinach was recorded. After fixed planting and grouping, plant height measurements were conducted on the 2nd, 9th, 16th, 23rd, 30th, and 37th days, respectively. The probes of the illuminance sensor were arranged on the top leaves, with 8 random measuring points set in each group, and data were recorded at 1 h intervals. Meanwhile, a movable cultivation frame (also designed by Light Environment Innovation Group) was used to record the leaf surface illumination data when the plant leaves were 10 cm, 20 cm, and 30 cm away from the LED lamps. All data were collected and recorded by a large-scale data logger (CR1000X; Campbell Scientific, Inc., Logan, UT, USA). The experiment was repeated 3 times.

2.2.2. Simulation Process of Leaf Surface Light Environment Establishment of Spinach Model

First step: A real image of spinach was selected as a reference for modeling. A spinach leaf was chosen, and the dimensional data of the leaf's shape, as well as relevant data such as the length and thickness of the stem, were recorded. A reference plane was selected in SolidWorks (SOLIDWORKS 2018), and based on the recorded data, the outline of the spinach leaf was sketched within the reference plane. Then, the 3D model of the spinach leaf was generated using the extrusion function in SolidWorks, as shown in Figure 2a,b. Regarding the spinach stem, first sketch the cross-sectional contours of both the top and bottom ends of the spinach stem, add a guide path along the height direction of the stem, and use the lofting function in SolidWorks to generate the 3D model of the stem, as shown in Figure 2c,d.

Second step: Based on the actual images of spinach, compare the size and shape of two actual spinach leaves as well as the length and thickness of their stems. According to the differences between the two actual spinach leaves, on the basis of the first spinach leaf model, adjust the size and shape of the leaf as well as the length and thickness of the stem to draw the second spinach leaf model. Repeat this modeling step to create the remaining spinach leaf models.

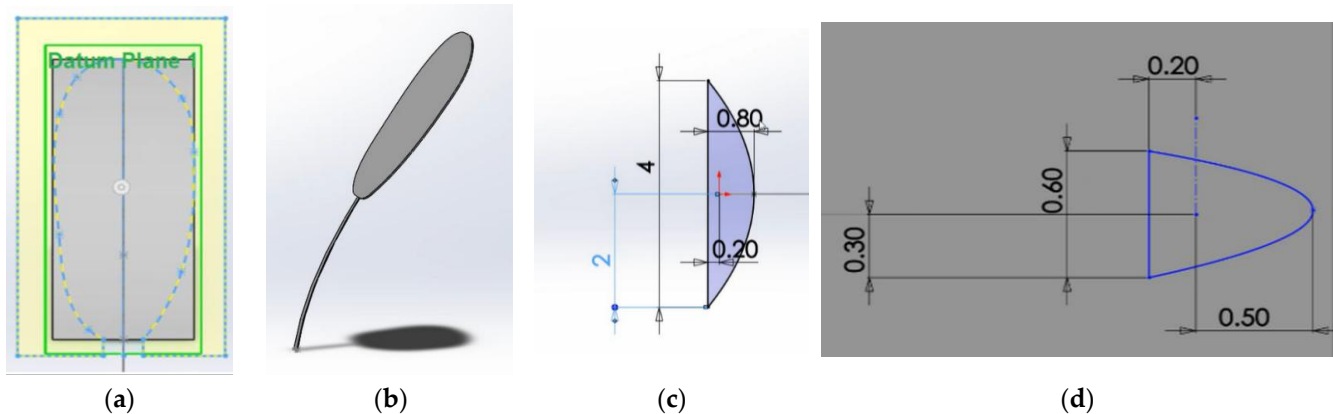


Figure 2. Sketch of Spinach Leaf and Stem: (a) contour of spinach leaf, (b) single leaf model, (c) contour of the stem base, and (d) contour of the stem top.

Third step: Assemble all the created spinach leaf models together according to the actual images of spinach to form an integral spinach model, and color it, as shown in Figure 3.



Figure 3. Overall model of spinach: (a) schematic diagram of spinach compound leaf assembly, (b) completed diagram of the model.

All models were constructed in batches and multiple times according to the growth stages of spinach leaves, in conjunction with plant height measurements, for subsequent use in illuminance simulation.

Establishment of the LED Lamp Model

First, based on the length, width, and height of the LED lamp and lamp beads, a cross-sectional contour was drawn, respectively, and then the 3D graphics were generated using the extrusion function, as shown in Figure 4a,b. Secondly, the LED lamp body, lampshade, and lamp bead models were built accordingly. Then, based on the side width of the LED lamp and lampshade, the side cover model was constructed, as shown in Figure 4c,d. Next, the assembly model of each component was established. During the assembly process, the LED lamp body model was first taken out, and then all lamp beads were installed on one side of the LED lamp body model at equal distances according to the required number of lamp beads. Then, the lampshade was installed on the same side as the lamp beads, and finally, the side covers were assembled, as shown in Figure 4e,f.

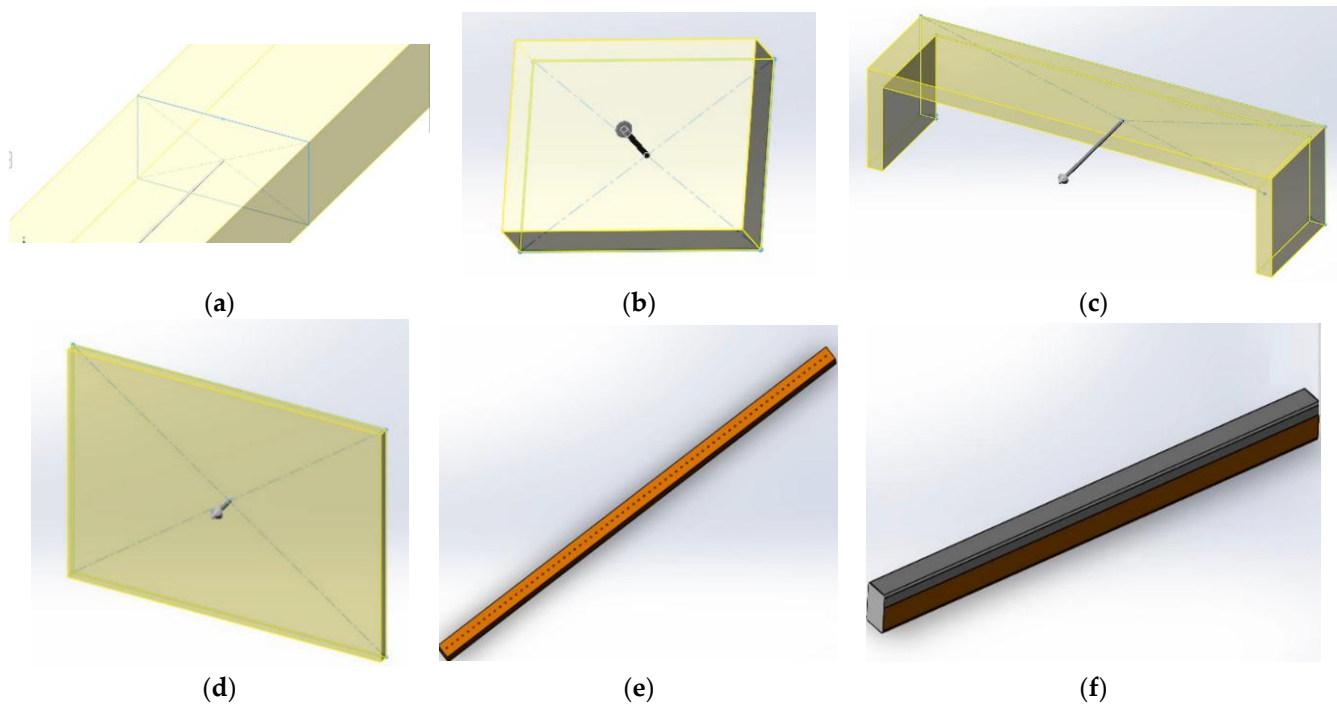


Figure 4. Composition diagram of the LED lamp model: (a) outline of the LED lamp, (b) outline of the lamp bead, (c) outline of the lampshade, (d) outline of the side cover, (e) schematic diagram of lamp bead assembly, (f) completed model of the LED lamp.

Setting of lampshade material, calculation of extinction coefficient, and determination of light propagation loss

The material of the lamp beads was defined and edited according to Wen et al. [27], as shown in Table 1 (a full-spectrum LED lamp was used with a transmittance of approximately 0.9). The temperature was set to 300 K, and the light wavelengths were set to four types: 0.4 μm , 0.5 μm , 0.6 μm , and 0.7 μm . The absorption value was set to 0.008 mm, and the extinction coefficients for each wavelength were obtained according to Beer–Lambert Law:

$$A = \varepsilon cL \quad (1)$$

Table 1. Properties of lamp bead material.

Wavelength (μm)	Temperature (K)	Absorption Value (mm)	Extinction Coefficient ($\text{L} \cdot \mu\text{mol} \cdot \mu\text{m}^{-1}$)
0.4	300	0.008	2.546
0.5	300	0.008	3.183
0.6	300	0.008	3.819
0.7	300	0.008	4.456

In the formula, A is the absorbed light intensity, ε is the molar extinction coefficient or molar absorption coefficient ($\text{L} \cdot \text{mol} \cdot \text{cm}^{-1}$), c is the content of the light-absorbing substance ($\text{mol} \cdot \text{L}^{-1}$), and L is the optical path length (cm).

The parameters of the overall LED lampshade material are shown in Table 2. Based on Table 1 and design standards, the wavelength of the LED lampshade was 0.5461, the refractive index was approximately 1.59, the absorption coefficient was 0.008, and the transmittance was around 0.9 (according to Beer–Lambert Law)

$$T = 10^{-A} \quad (2)$$

Table 2. Parameters of the lampshade material.

Wavelength (μm)	Refractive Index	Absorption Coefficient	Transmittance
0.5461	1.59	0.008	0.92

In the formula, T is the transmittance, and $1 - T$ is the proportion of absorbed light.

The index values calculated above meet the target values. To simplify the modeling process, the transmittance of the opaque parts of the spinach and LED lamp models was set to 0.

Setting of light source parameters on the surface of lamp beads.

According to Zheng et al. [24], first, set the emission form of 72 lamp beads as luminous flux, with the unit being photometry. The minimum number of light rays is set to 10, the total number of light rays is set to 5000, the field angle distribution is the Lambertian luminous field type, and the luminous flux is 25 lumens. Then, set different wavelengths, respectively: Divide the 72 lamp beads into 18 groups, with every 4 lamp beads numbered 1, 2, 3, and 4; then, group the lamp beads with the same number in the 18 groups into a large group, totaling 4 large groups. The wavelength of the lamp beads in the first large group is set to $0.45 \mu\text{m}$ (since the wavelength of $0.4 \mu\text{m}$ exceeds the effective wavelength range of the plastic material ($0.4358 \mu\text{m}$ – $1.052 \mu\text{m}$), the wavelength of the first group of lamp beads is set to $0.45 \mu\text{m}$), the second large group to $0.5 \mu\text{m}$, the third large group to $0.6 \mu\text{m}$, and the fourth large group to $0.7 \mu\text{m}$. The luminous flux of each group is set to 25 lm. The minimum number of light rays of each group is set to 10 strips and the total number of light rays of is set to 5000 strips.

2.3. Data Statistics and Analysis

Data analysis was performed using SPSS 27.0 software and GraphPad Prism 9.5.0 software, and the experimental data (including plant morphology data, simulation, and actual measurement of light intensity) were analyzed by Tukey's HSD test. A paired two-sample t -test was conducted to compare the measured and simulated values with TracePro under different distances from the light source.

3. Results

3.1. Data on Changes in Spinach Plant Height and Measurements of Leaf Surface Illuminance

Four planned spinach cultivations, T1 (equal difference), T2 (rectangle), T3 (hexagon), and T4 (diamond), were investigated for leaf surface illuminance. After the spinach grew 2–3 true leaves, the average plant height of 4 groups of spinach was recorded every 8 days (Figure 5), and the illuminance on the leaf surfaces of the 4 groups of spinach was measured. The average illuminance of spinach with four planting arrangements under different plant heights is shown in Table 3. It can be seen from the data in the table that under the light-controlled conditions with the same output, the four planting arrangements resulted in different growth and development statuses of spinach, and the light received by the leaf surfaces also varied. In general, the plant height in the T2 group increased relatively rapidly, though some data in other groups showed no significant difference; for example, some plant height in T3, the absolute value of the T2 group is highest. Using the regression equations of plant height of each group shown in Figure 5 and combining them with the light integral formula, it is inferred that under the same height, the light received by the leaves in the T2 group and T3 group partially was significantly higher than that in other groups at the same height, leading to a faster increase in plant height (Table 3 and Figure 5).

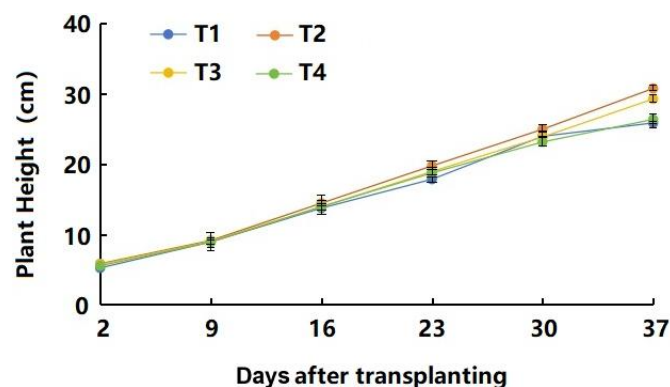


Figure 5. Changes in spinach plant height of T1 (equal difference), T2 (rectangle), T3 (hexagon), and T4 (diamond). The data of the four treatments were compared within the same number of days. Bars represent mean $\pm$ SD ($n = 3$).

Table 3. Average illuminance on spinach leaf surfaces under four cultivation arrangements at different plant heights (Klux).

Treatment	10 cm	15 cm	20 cm	25 cm
T1 ¹	3.42 ± 0.18 b ²	4.42 ± 0.31 c	6.45 ± 0.25 b	7.31 ± 0.21 c
T2	3.53 ± 0.29 a	4.81 ± 0.33 a	6.54 ± 0.29 a	7.91 ± 0.21 a
T3	3.48 ± 0.22 ab	4.80 ± 0.39 a	6.52 ± 0.27 a	7.72 ± 0.24 b
T4	3.45 ± 0.29 b	4.76 ± 0.22 b	6.43 ± 0.30 b	7.65 ± 0.31 b

¹ Four cultivation-planned spinach, T1 (equal difference), T2 (rectangle), T3 (hexagon), and T4 (diamond), were investigated for leaf surface illuminance. ² Different letters in each plant height indicate statistically significant differences according to Tukey's HSD test at $p < 0.05$.

3.2. Modeling of Leaf Surface Light Environment Under Different Spinach Cultivation Arrangements

Three optical simulation software programs, namely TracePro, LightTools, and Ansys Lumerical FDTD Solution, were used to perform ray tracing analysis on spinach models under four planting arrangements, with the results shown in Figures 6–8. Since lux is the output unit of the software, no other unit conversion was performed on the results of this experiment to ensure the effectiveness of data statistics.

For the T1 arrangement simulated by TracePro software, the maximum illuminance on the leaf surface was approximately 3362 lux, and the average value was about 1748.3 lux (Figure 6a); for the T2 arrangement, the maximum illuminance on the leaf surface was around 3339 lux, with an average of about 1729 lux (Figure 6b); for the T3 arrangement, the maximum illuminance on the leaf surface was roughly 3976 lux, and the average was approximately 1433.8 lux (Figure 6c); for the T4 arrangement, the maximum illuminance on the leaf surface was about 5909.9 lux, with an average of around 988.16 lux (Figure 6d).

For the T1 arrangement simulated by LightTools software, the maximum illuminance on the leaf surface is approximately 3142 lux, with an average of about 2078.3 lux (Figure 7a); for the T2 arrangement, the maximum illuminance on the leaf surface is around 2939 lux, and the average is about 2029 lux (Figure 7b); for the T3 arrangement, the maximum illuminance on the leaf surface is roughly 2786 lux, with an average of approximately 1593.3 lux (Figure 7c); for the T4 arrangement, the maximum illuminance on the leaf surface is about 2409.9 lux, and the average is around 1298.01 lux (Figure 7d).

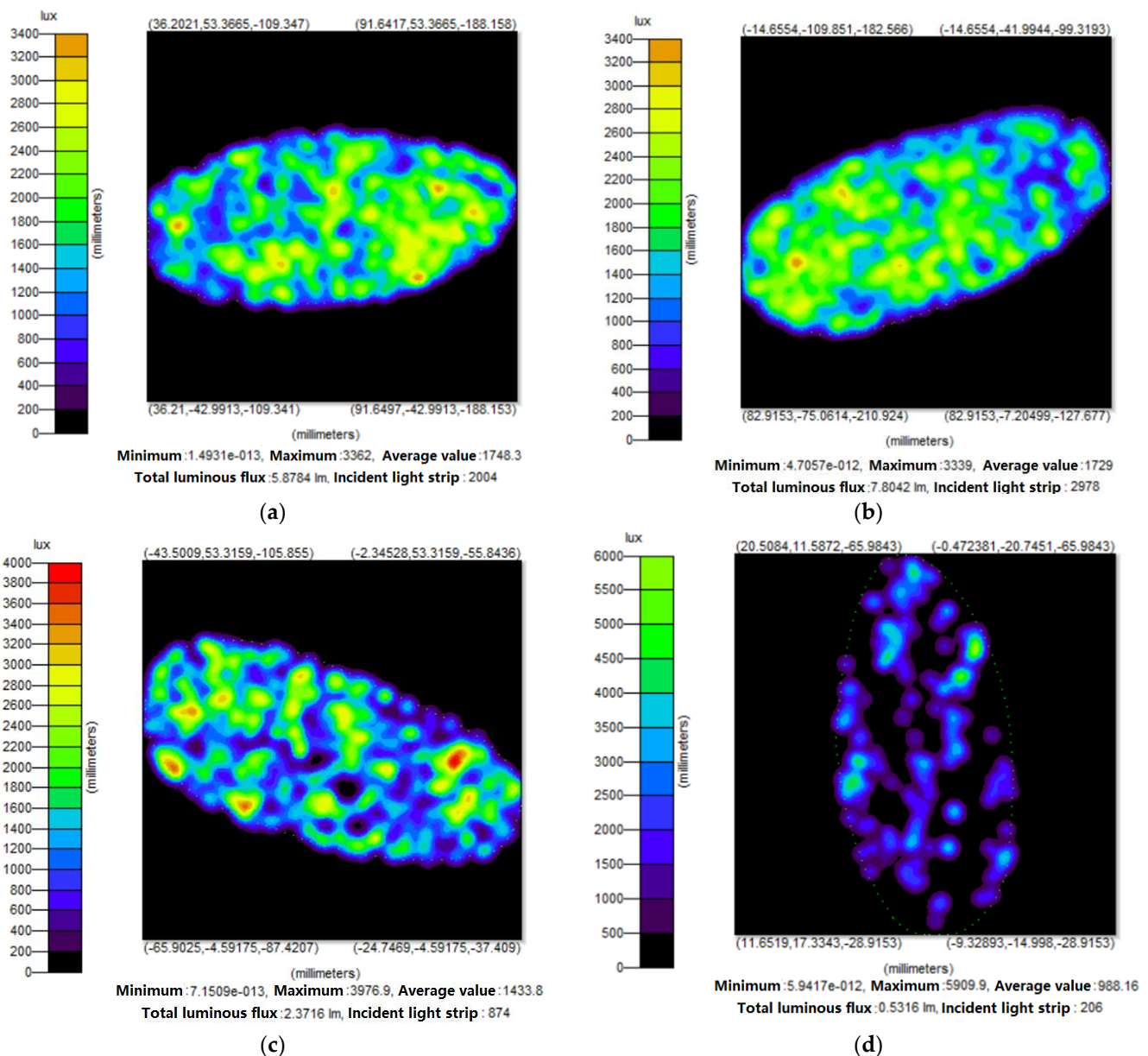


Figure 6. Illuminance on spinach leaf surfaces under different treatments simulated by TracePro: (a) T1 (equal difference), (b) T2 (rectangle), (c) T3 (hexagon), and (d) T4 (diamond).

The data heatmap output method of Ansys Lumerical FDTD Solution is slightly different from the above two software. For the T1 arrangement simulated by this software, the peak illuminance on the leaf surface is approximately 694.18 cd, and the average luminous flux is about 1758.9 lux (Figure 8a); for the T2 arrangement, the peak illuminance on the leaf surface is around 690.16 cd, with an average luminous flux of about 1731 lux (Figure 8b); for the T3 arrangement, the peak illuminance on the leaf surface is roughly 712.06 cd, and the average luminous flux is approximately 1430 lux (Figure 8c); for the T4 arrangement, the peak illuminance on the leaf surface is about 694.18 cd, with an average luminous flux of around 1030.8 lux (Figure 8d).

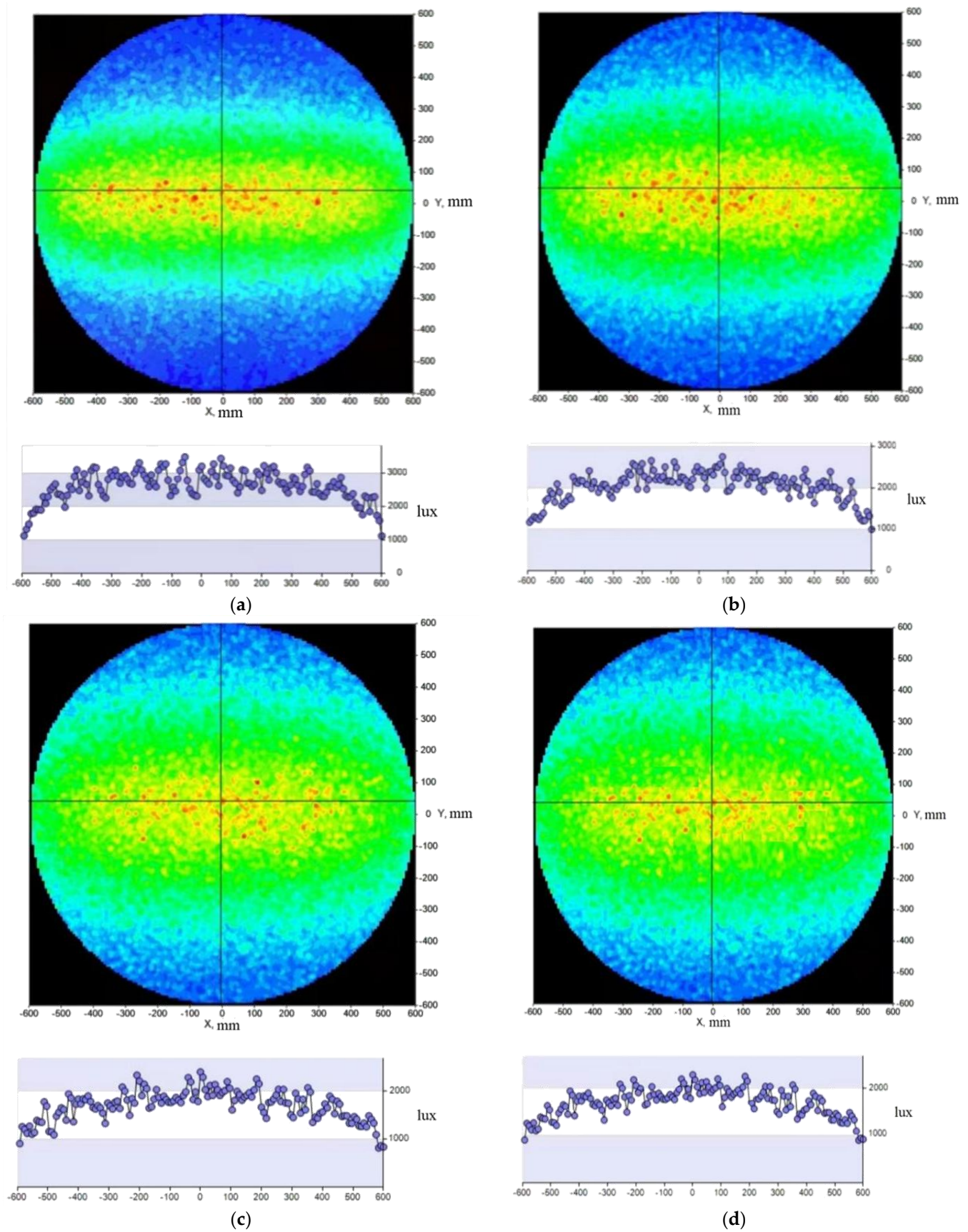


Figure 7. Illuminance on spinach leaf surfaces under different treatments simulated by Light Tools: (a) T1 (equal difference), (b) T2 (rectangle), (c) T3 (hexagon), and (d) T4 (diamond).

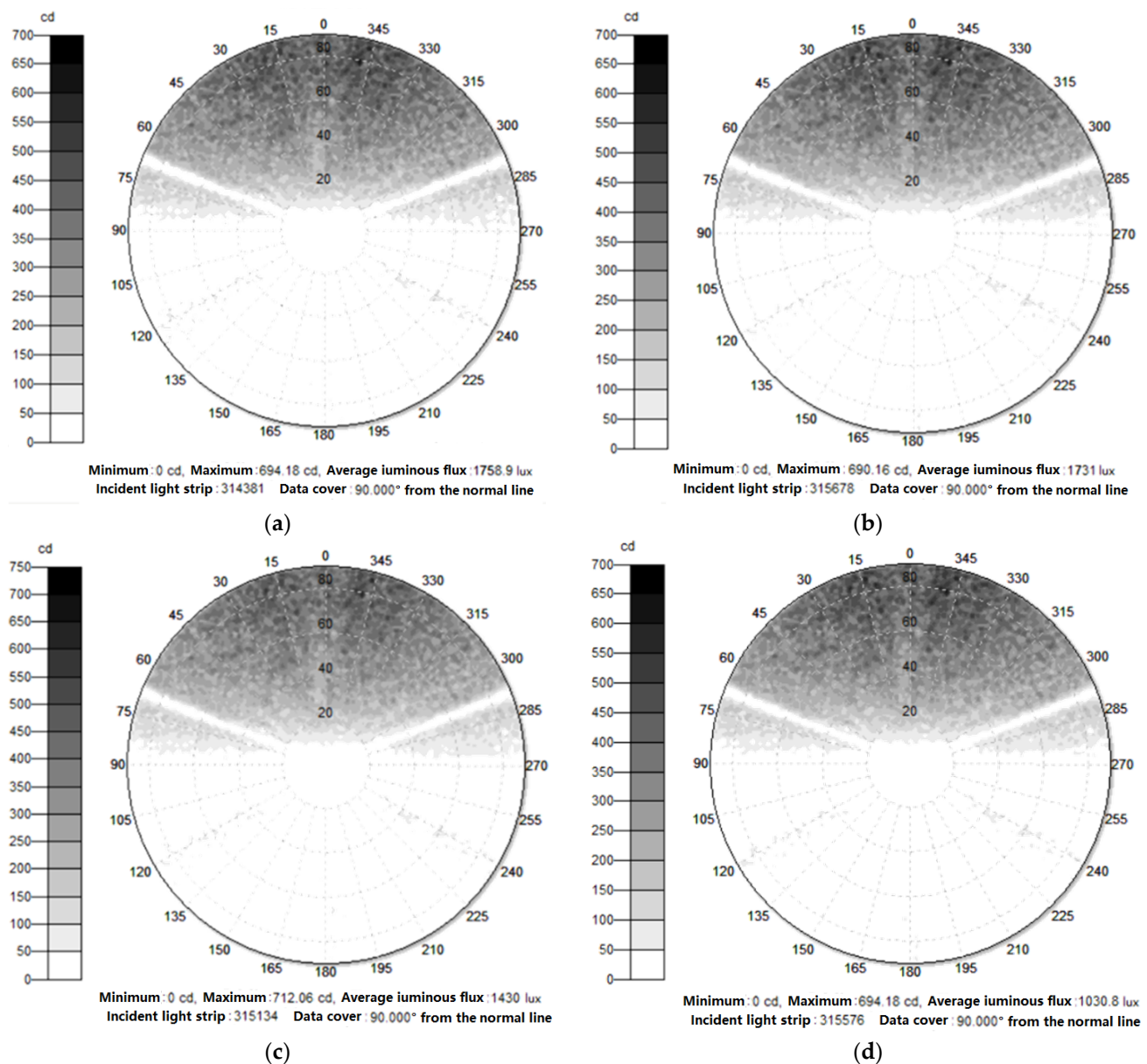


Figure 8. Illuminance on spinach leaf surfaces under different treatments simulated by Ansys Lumerical FDTD Solution: (a) T1 (equal difference), (b) T2 (rectangle), (c) T3 (hexagon), and (d) T4 (diamond).

Although the output units of illuminance among the three software may vary, it can be known through conversion that after unifying to lux, there is no cross-order-of-magnitude difference, indicating that their simulated values can be compared. In general, for the same software, the 3D heatmaps of illuminance analysis for spinach models under different planting arrangements tend to be consistent, which shows that the differences in planting arrangements have little impact on the software modeling itself. However, under different planting arrangements, there are differences in the 3D heatmaps of illuminance analysis, indicating that there are differences in the modeling results of different software.

Table 4 shows the comparison between the simulated values from the three software and the measured values of leaf surface illuminance under the four cultivation arrangements. Among all treatments, only the data from TracePro consistently showed no significant difference from the measured values. Meaning among them, the difference between the simulated values and the measured values under various cultivation arrangements obtained by TracePro simulation software is the smallest.

Table 4. Simulation and actual measurement of light intensity on spinach leaf surfaces under four cultivation arrangements (Klux).

Treatment	Measured Value	TracePro	Light Tools	Ansys Lumerical FDTD Solution
T1	1.71 ± 0.12 ab ¹	1.75 ± 0.18 a	1.65 ± 0.03 b	1.66 ± 0.41 b
T2	1.77 ± 0.23 a	1.77 ± 0.31 a	1.57 ± 0.30 c	1.74 ± 0.19 b
T3	1.41 ± 0.11 b	1.43 ± 0.05 b	1.50 ± 0.24 a	1.43 ± 0.22 b
T4	1.00 ± 0.53 bc	0.99 ± 0.06 c	1.29 ± 0.32 a	1.03 ± 0.84 b

¹ Different letters in each treatment indicate statistically significant differences according to Tukey's HSD test at $p < 0.05$.

3.3. Modeling of the Light Environment on Spinach Leaf Surfaces Under Different Light Source Distances

Based on the results from Sections 3.1 and 3.2, we investigated the illuminance on the leaf surfaces of spinach models using TracePro under a rectangular planting arrangement at distances of 10 cm, 20 cm, and 30 cm from the LED lamps (Figure 9 and Table 5). When the distance from the lamps was 10 cm, the average illuminance of the leaf model was 3068.3 lux, with a total of 3815 incident light rays on the model surface, and the measured illuminance was 3112.8 lux. At a distance of 20 cm from the lamps, the average illuminance of the leaf model was 2365.2 lux, with 2838 incident light rays on the model surface, and the measured illuminance was 2417.8 lux. When the distance was 30 cm from the lamps, the average illuminance of the leaf model was 1775.8 lux, with 2130 incident light rays on the model surface, and the measured illuminance was 1812.2 lux.

Table 5. Simulated and measured values of average illuminance on spinach leaf surfaces under different light source distances (Klux).

	10 cm	20 cm	30 cm
Measured values	3.11 ± 0.12	2.42 ± 0.11	1.81 ± 0.35
Simulated values	3.07 ± 0.23	2.37 ± 0.27	1.78 ± 0.04

A one-sample t -test was conducted between the measured values at the three distances and the simulated values from TracePro software, with the results shown in Table 6. It can be seen that since the p -value is greater than the significance level of 0.05, there is insufficient evidence to reject the null hypothesis, indicating no statistically significant difference between the measured and simulated values. Moreover, when the light source distance is 30 cm, the resulting p -value of 0.977 is the highest.

Table 6. One-sample t -test of TracePro simulated values under different light source distances.

	10 cm	20 cm	30 cm
Confidence interval	−0.225, 0.145	−0.144, 0.257	−0.342, 0.441
Significance	0.884	0.928	0.977

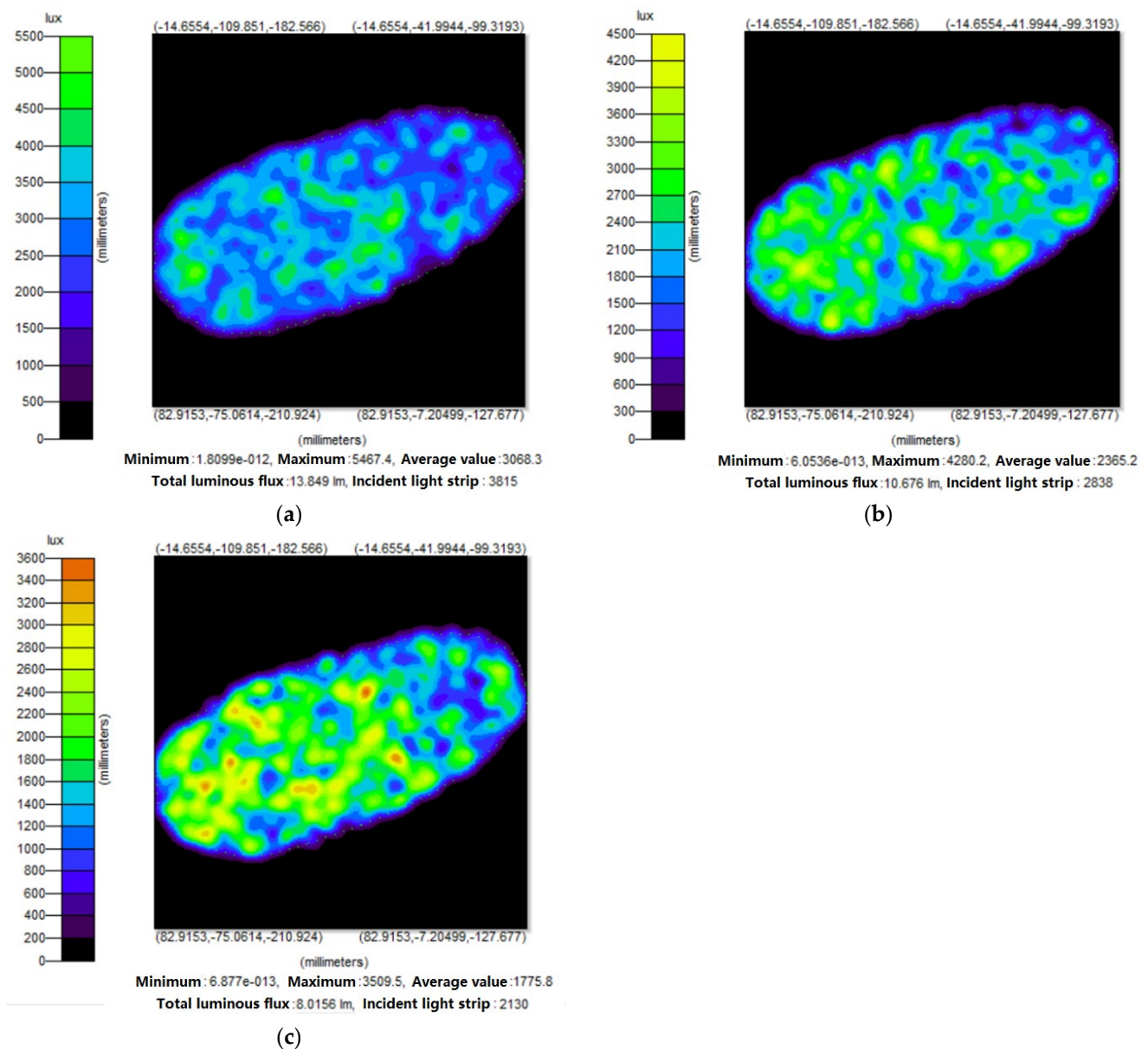


Figure 9. Analysis chart of illuminance on spinach leaf surfaces under different distances from light sources: (a) 10 cm, (b) 20 cm, (c) 30 cm.

4. Discussion

In this study, under the T2 rectangular cultivation arrangement, spinach leaves received more light, and the plants grew faster. This indicates that for strip-arranged LED light sources, the rectangular, i.e., evenly distributed, planting method is more conducive to the effective light energy reception by plant leaves. Under this mode, it is more beneficial for leaf photosynthesis, thereby achieving more material accumulation. This is consistent with previous research results [6].

When examining different plant planting arrangements, it was found that they had little impact on the simulation results of the same software. However, under the same planting arrangement, there were significant differences in the simulation results among the three software, among which the difference between the simulated values of TracePro and the measured values was the smallest. This should be caused by the differences in the degree of fuzzy calculation and robustness of different software for the light-receiving surface of plants. Previous studies have reported that when using different lighting analysis

software and various algorithms to optimize the design of such items as LED lamp beads and array light sources, it was found that the square array arrangement under the particle swarm optimization algorithm is more suitable for plant lighting compared with circular and triangular arrays [31,32]. However, the results are only applicable to surface light sources. For mixed-color light sources, low illumination uniformity can lead to light spots on the illuminated surface at close range [32], thereby resulting in inconsistent growth light environments of the same batch of plants calculated by different software that mainly rely on direct light intensity calculation.

Further tracking and simulation of the leaf surface illuminance of spinach under the rectangular planting arrangement at different distances from the lamps using TracePro showed high accuracy, indicating that TracePro simulation software is most suitable for monitoring the changes in the light environment during spinach growth in plant factories. In our study, although the confidence intervals suggest that the difference may be close to zero (indicating no significant difference), a paired *t*-test was conducted to verify statistical significance, and the resulting *p*-value of 0.977 (when the light source distance is 30 cm) indicates no significant difference between the measured and simulated values. This demonstrates the strong application potential of this software. Based on a previous report, TracePro adopts the Monte Carlo ray tracing method, which can ensure that light rays on the surface of objects can be correctly analyzed [28]. In addition, he also pointed out that TracePro can not only edit multiple models in one program but also import model data from CAD software, providing conditions for the establishment of complex models [29]. Combined with its relatively simple operation interface design, the optical analysis function of TracePro is more suitable for application scenarios requiring intuitive simulation and rapid monitoring and should have good adaptability to the intelligent monitoring of various factors in the production environment of plant factories. In recent years, with the rapid development of smart agricultural production, high-fidelity imaging of the production environment has become an indispensable part of the monitoring process in intelligent production. When optical software is combined with new high-fidelity imaging transmission composite materials, it can maintain high imaging quality while transmitting a large amount of image data [33–36], which meets the requirements for imaging detail accuracy and data volume in various aspects such as crop phenotype monitoring and environmental data visualization in smart horticultural crop production.

In recent years, the digital plant revolution, represented by breakthroughs in high-definition imaging technology, has quietly arrived [37–47]. Various research achievements not only involve real-time monitoring and early warning of many aspects such as the growth [38], pollination [39], and diseases [40] of field crops like corn [41], rice [42,43], and wheat [44], but also their applications in the field of horticultural plants have gradually become popular [45–47]. In practical production applications, to find the most suitable illuminance for spinach growth, corresponding plant models and lamp models can be created using software, and a corresponding model library can be established for easy call-up at any time. Ray tracing analysis can be carried out with models created on demand, and the illuminance of spinach can be observed and analyzed through intuitive heatmaps. This study shows that this digital plant analysis method is fast and accurate, can intuitively present the illuminance on spinach leaf surfaces, and can provide rapid environmental monitoring data for spinach production in plant factories. Meanwhile, with the rapid development of smart agricultural production, high-fidelity imaging of the production environment has become an indispensable part of the monitoring process in intelligent production. When optical software is combined with new high-fidelity imaging transmission composite materials, it can maintain high imaging quality while transmitting a large amount of image data, which meets the requirements for imaging

detail accuracy and data volume in various aspects such as crop phenotype monitoring and environmental data visualization in smart horticultural crop production. In this study, we investigated the surface light irradiation with software simulation. Though the software has considered the possible shade effect, most light rays were defined as direct rays, which might decrease the actual irradiation amount with the missing of scattered radiation. This means we need extra consideration of the light state in different canopies with digital optical technology developed. Meanwhile, the concept of light ray visualization attempts also can be applied to other plant production in plant factories, greenhouses, plastic tunnels, and even field production scenes. For example, when a greenhouse-produced high-quality cherry tomato turns to the third or fourth truss, irradiation exposure on both function leaves (mainly contributing to fruit enlargement) and fruit (quality formation) decreases significantly. Growers can adjust artificial light sources more intelligently (including supplemental lighting position, cycle, quantity, spectrum, etc.), thereby ensuring the high-quality production of products and high economic returns. The application of this ray tracing technology and optical simulation software in vegetable production will reduce labor input and time costs in production and promote the intelligentization of horticultural production. At the same time, during the modeling process of this study, it was found that none of the three software has a plant database, and the simulation process often takes a lot of time. This suggests that future research can focus on the establishment of general databases for various common horticultural crops so as to provide references for the standardization of digital technologies in smart horticultural plants.

5. Conclusions

In this paper, LightTools, TracePro, and Ansys Lumerical FDTD Solution are selected as the research objects to investigate their performance in simulating the light environment of a spinach leaf surface under different planting arrangements and different lamp source distances. Under the rectangular planting arrangement, the absolute value of illuminance was highest, indicating the leaves received more light, and the plants grew faster. Different plant planting arrangements had different impacts on the simulation results of the same software; there were significant differences between simulated value and measured value under rectangular planting arrangements and hexagonal planting arrangements with Light Tools. In addition, there were significant differences in the simulation results among the three software under the same planting arrangement, among which the difference between the simulated values of TracePro and the measured values was the smallest. When using TracePro, there was no significant difference between the simulated values of the software and the measured values, and the simulation accuracy was the highest when the distance from the light source was 30 cm.

Author Contributions: Conceptualization, C.J. and Y.S.; methodology, M.L. and T.P.; software, K.Z. and Y.M.; validation, K.Z. and Y.M.; formal analysis, M.L.; investigation, K.Z.; resources, Y.Z.; data curation, K.Z.; writing—original draft preparation, C.J. and Y.Z.; writing—review and editing, K.Z., Y.M. and T.P.; project administration, C.J. and W.L.; funding acquisition, Y.S. and W.L. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Major Science and Technology Project of Xinjiang Uygur Autonomous Region (2022A02005-2), the National Science Foundation of China (32202581), and Independent Cultivation Project of Research Institute of Crop Germplasm Resources, Xinjiang Academy of Agricultural Sciences: PZ202302.

Institutional Review Board Statement: Not applicable.

Data Availability Statement: The original contributions presented in this study are included in the article. Further inquiries can be directed to the corresponding authors.

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

References

1. Zou, T.; Huang, C.; Wu, P.; Ge, L.; Xu, Y. Optimization of artificial light for spinach growth in plant factory based on orthogonal test. *Plants* **2020**, *9*, 490. [[CrossRef](#)] [[PubMed](#)]
2. Cai, X.; Ge, C.; Wang, X.; Xu, C.; Wang, Q. Advances and perspectives in research of spinach breeding technology in China. *Jiangsu J. Agric. Sci.* **2019**, *35*, 996–1005. (In Chinese)
3. Akbari, F.; Mollaei, M.; Argani, P.; Daneshfard, B.; Derakhshan, A.R. *Spinacia Oleracea*: Exploring the therapeutic potential in persian medicine and modern pharmacology. *Curr. Drug Discov. Technol.* **2024**, *21*, e150224227025. [[CrossRef](#)] [[PubMed](#)]
4. Pan, Y.; Xu, X.; Lang, Q.; Liao, S.; Li, Y. Three different fertilizers enhance spinach growth and reduce spinach Cd concentration in Cd contaminated Alkaline Soil. *Horticulturae* **2023**, *9*, 445. [[CrossRef](#)]
5. Vatistas, C.; Avgoustaki, D.D.; Monedas, G.; Bartzanas, T. The effect of different light wavelengths on the germination of lettuce, cabbage, spinach and arugula seeds in a controlled environment chamber. *Sci. Hort.* **2024**, *331*, 113118. [[CrossRef](#)]
6. Semenova, N.A.; Proshkin, Y.A.; Smirnov, A.A.; Dorokhov, A.S.; Ivanitskikh, A.S.; Burynin, D.A.; Dorokhov, A.A.; Uyutova, N.I.; Chilingaryan, N.O. The influence of the spectral composition and light intensity on the morphological and biochemical parameters of spinach (*Spinacia oleracea* L.) in vertical farming. *Horticulturae* **2023**, *9*, 1130. [[CrossRef](#)]
7. Ming, Z.; Lyu, Q.; Ming, Y.; Zeng, W.; Lyu, H.; Zhang, J. Optimization of LED light source array based on improved particle swarm algorithm. *J. Appl. Opt.* **2022**, *43*, 524. [[CrossRef](#)]
8. Fang, Y.C.; Tzeng, Y.F.; Li, S.X. Multi-objective design and extended optimization for developing a miniature light emitting diode pocket-sized projection display. *Opt. Rev.* **2008**, *15*, 241–250. [[CrossRef](#)]
9. Kozai, T. Plant factory in Japan-current situation and perspectives. *Chron. Horticult.* **2013**, *53*, 8–11.
10. Bourget, C.M. An introduction to light-emitting diodes. *Hortscience* **2008**, *3*, 1944–1946. [[CrossRef](#)]
11. Morrow, R.C. LED lighting in horticulture. *Hortscience* **2008**, *43*, 1947–1950. [[CrossRef](#)]
12. Kim, K.C.; Lee, J.; Kim, H.J.; Koo, D.H. Multiobjective optimal design for interior permanent magnet synchronous motor. *IEEE Trans. Magn.* **2009**, *45*, 1780–1783. [[CrossRef](#)]
13. Hwang, C.C.; Lyu, Y.; Liu, C.T.; Li, P.L. Optimal design of a spm motor using genetic algorithms and Taguchi method. *IEEE Trans. Magn.* **2008**, *44*, 4325–4328. [[CrossRef](#)]
14. Silva, M.M.A.; Oliveira, A.L.B.D.; Oliveira-Filho, R.A.; Gouveia-Neto, A.S.; Camara, T.J.R.; Willadino, L.G. Effect of blue/red LED light combination on growth and morphogenesis of *saccharum officinarum* plantlets in vitro. *SPIE* **2014**, *8947*, 342–348.
15. Zhang, S.; Ma, J.; Zou, H.; Zhang, L.; Li, S.; Wang, Y. The combination of blue and red LED light improves growth and phenolic acid contents in *Salvia miltiorrhiza* Bunge. *Ind. Crops Prod.* **2020**, *158*, 112959. [[CrossRef](#)]
16. Mitsanis, C.; Hurst, W.; Tekinerdogan, B. A 3D functional plant modelling framework for agricultural digital twins. *Comput. Electron. Agric.* **2024**, *218*, 108733. [[CrossRef](#)]
17. Onwude, D.; North, J.; Cronje, P.; Schouten, R.; Defraeye, T. Digital twins to quantify the impact of growing variability on the harvest quality of orange. *Sci. Hort.* **2024**, *331*, 113129. [[CrossRef](#)]
18. Ganapathysubramanian, B.; Sarkar, S.; Singh, A.; Singh, A.K. Digital twins for the plant sciences. *Trend Plant Sci.* **2025**, *30*, 576–577. [[CrossRef](#)]
19. Teek, S.L.; Chen, S.X.; Gao, X.K. Robusttorque optimization for BLDC spindle motors. *IEEE Trans. Ind. Electron.* **2001**, *48*, 656–663.
20. Moreno, I. Illumination uniformity assessment based on human vision. *Opt. Lett.* **2010**, *35*, 4030–4032. [[CrossRef](#)]
21. Sun, C.C.; Moreno, I.; Lo, Y.C.; Chiu, B.C.; Chien, W.T. Collimating lamp with well color mixing of red/green/blue LEDs. *Opt. Express* **2012**, *20*, 75–84. [[CrossRef](#)]
22. Liu, P.; Wang, H.; Wu, R.; Yang, Y.; Zhang, Y.; Zheng, Z.; Li, H.; Liu, X. Uniform illumination design by configuration of LEDs and optimization of LED lens for large-scale color-mixing applications. *Appl. Opt.* **2013**, *52*, 3998–4005. [[CrossRef](#)]
23. Wang, H.C.; Chiang, Y.T.; Lin, C.Y.; Lu, M.Y.; Lee, M.K.; Feng, S.W.; Kuo, C.T. All-reflective RGB LED flashlight design for effective color mixing. *Opt. Express* **2016**, *24*, 266–271. [[CrossRef](#)] [[PubMed](#)]
24. Zheng, Z.; Ma, Z.; Li, R.; Wei, H.; Chu, X.; Liu, H. Design method for improving illumination distribution uniformity of LED plant growth light source. In Proceedings of the 2021 18th China International Forum on Solid State Lighting & 2021 7th International Forum on Wide Bandgap Semiconductors (SSLChina: IFWS), Shenzhen, China, 6–8 December 2021; pp. 202–210.
25. Wang, D.; Zou, J.; Luo, S.; Liu, W.; Li, Y.; Shi, M.; Li, Y.; Wang, Z.; Wang, Y.; Chen, Q.; et al. Study on uniformity and thermal stability of strip LED lamps in pea growing applications. *Measurement* **2025**, *245*, 116604. [[CrossRef](#)]
26. Zhang, S.; Wen, S.; Ma, B.; Pang, P.; Chen, H.; Cai, M.; Fu, M.; Hou, Y.; Zou, X. High uniformity LED panel-light for plant lighting. *Chin. J. Lumin.* **2018**, *39*, 403–413. [[CrossRef](#)]
27. Wen, Z.; Luo, S.; Zhu, L.; Wei, H.; Cai, S.; Li, M.; Ma, Z. Optimization and verification of the arrangement of lamp beads for LED light source for plant growth based on TracePro. *J. Zhongkai Univ. Agric. Eng.* **2020**, *33*, 44–49, (In Chinese with English Abstract).
28. Pan, G.; Wu, K.; Zhou, J. Application study of TracePro in LED lighting design. *J. Chizhou Univ.* **2023**, *37*, 16–18. (In Chinese)

29. Zhang, H.; Jiang, M.; Jia, D.; Shi, Y.; Zhang, L. Simulation design for teaching multimode fiber imaging features based on TracePro modeling. *Intel. Comp. Appl.* **2025**, *7*, 1–11. (In Chinese with English Abstract)
30. Zhang, Y.; Zhu, C.; Zhang, R. Simulation experiment of electromagnetic properties in metallic rectangle waveguide based on FDTD Solutions. *Exp. Tech. Manag.* **2020**, *37*, 161–165.
31. Deng, Y.; Xu, X.; Su, Y.; Song, T.; Wang, L.; Fang, Z. Study on design and uniformity of LED plant tissue culture array. *Jiangsu Agri. Sci.* **2017**, *45*, 225–228. (In Chinese)
32. Tang, H.; Wen, S.; Fu, M.; He, G.; Zhang, H.; Liao, S.; Kang, L. Design of LED plant lighting source based on particle swarm optimization algorithm under photons system. *Chin. J. Lumi.* **2019**, *40*, 340–348. (In Chinese)
33. Psaltis, D.; Moser, C. Imaging with multimode fibers. *Opt. Photonics News* **2016**, *27*, 24–31. [[CrossRef](#)]
34. Rehan, M.; Chowdhury, R.; Biswas, P.; Kang, M.S.; Varshney, S.K. Low-threshold cascaded Raman scattering and intermodal four-wave mixing in cascaded multimode fiber system. *J. Light. Technol.* **2024**, *42*, 4636–4642. [[CrossRef](#)]
35. Rahmani, B.; Oguz, I.; Tegin, U.; Hsieh, J.; Psaltis, D.; Mose, C. Learning to image and compute with multimode optical fibers. *Nanophotonics* **2022**, *11*, 1071–1082. [[CrossRef](#)] [[PubMed](#)]
36. Liu, Z.; Wang, L.; Meng, Y.; He, T.; He, S.; Yang, Y.; Wang, L.; Tian, J.; Li, D.; Yan, P.; et al. All-fiber high-speed image detection enabled by deep learning. *Nat. Commun.* **2022**, *13*, 1433. [[CrossRef](#)] [[PubMed](#)]
37. Ren, M.N.; Yu, X.J.; Mujumdar, A.S.; Yagoub, A.A.; Chen, L.; Zhou, C.S. Visualizing the knowledge domain of pulsed light technology in the food field: A scientometrics review. *Innov. Food Sci. Emerg. Technol.* **2021**, *74*, 102823. [[CrossRef](#)]
38. Tang, L.D.; Syed, A.U.; Otho, A.R.; Junejo, A.R.; Tunio, M.H.; Hao, L.; Ali, M.N.H.A.; Brohi, S.A.; Otho, S.A.; Channa, J.A. Intelligent papid asexual propagation technology-a novel aeroponics propagation approach. *Agronomy* **2024**, *14*, 2289. [[CrossRef](#)]
39. Wu, S.; Liu, J.Z.; Lei, X.J.; Zhao, S.Y.; Lu, J.J.; Jiang, Y.X.; Xie, B.B.; Wang, M. Research progress on efficient pollination technology of crops. *Agronomy* **2022**, *12*, 2872. [[CrossRef](#)]
40. Wan, L.; Li, H.; Li, C.S.; Wang, A.C.; Yang, Y.H.; Wang, P. Hyperspectral sensing of plant diseases: Principle and methods. *Agronomy* **2022**, *12*, 1451. [[CrossRef](#)]
41. Niu, Y.X.; Han, W.T.; Zhang, H.H.; Zhang, L.Y.; Chen, H.P. Estimating maize plant height using a crop surface model constructed from UAV RGB images. *Biosyst. Eng.* **2024**, *241*, 56–67. [[CrossRef](#)]
42. Sun, J.; Lu, X.Z.; Mao, H.P.; Wu, X.H.; Gao, H.Y. Quantitative determination of rice moisture based on hyperspectral imaging technology and BCC-LS-SVR algorithm. *J. Food Process Eng.* **2017**, *40*, e12446. [[CrossRef](#)]
43. Lu, X.Z.; Sun, J.; Mao, H.P.; Wu, X.H.; Gao, H.Y. Quantitative determination of rice starch based on hyperspectral imaging technology. *Int. J. Food Prop.* **2017**, *20*, S1037–S1044. [[CrossRef](#)]
44. Chen, X.X.; Tang, Y.L.; Duan, Q.F.; Hu, J.P. Phenotypic quantification of root spatial distribution along circumferential direction for field paddy-wheat. *PLoS ONE* **2023**, *18*, e0279353. [[CrossRef](#)] [[PubMed](#)]
45. Li, M.Q.; Li, J.Y.; Mao, H.P.; Wu, Y.Y. Diagnosis and detection of phosphorus nutrition level for *Solanum lycopersicum* based on electrical impedance spectroscopy. *Biosyst. Eng.* **2016**, *143*, 108–118. [[CrossRef](#)]
46. Yan, T.; Zhu, H.; Sun, L.; Wang, X.; Ling, P. Investigation of an experimental laser sensor-guided spray control system for greenhouse variable-rate applications. *Trans. ASABE* **2019**, *62*, 899–911. [[CrossRef](#)]
47. Wang, J.Z.; Zhang, Y.; Gu, R.R. Research status and prospects on plant canopy structure measurement using visual sensors based on three-dimensional reconstruction. *Agriculture* **2020**, *10*, 462. [[CrossRef](#)]

Disclaimer/Publisher’s Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.