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# Effects of Light Conversion Film on the Growth of Leafy Vegetables in Facilities under Haze Weather

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**Abstract:** The light intensity is low in haze weather, and the facility is in a weak light environment for a long time. As a functional film, light conversion film (LCF) can improve the light conversion performance and is conducive to regulating the environment in the facility to promote crop growth. It can be seen from the test that the light transmittance of LCF under visible light conditions (400–780 nm) is 8.67% higher than that of ordinary film (OF), with stronger light transmittance. In the red–orange light band (600–700 nm), the LCF is 1.3% higher than that of the OF. Through the detection of irradiance, it was found that the irradiance was outdoor environment > LCF > OF in any weather. A two-year greenhouse experiment was conducted to study the effect of LCF on the whole growth process of facility agriculture (environment-soil-crop) under weak light. It is found that LCF reduces the air humidity by 0.47~2.83%; it has an obvious warming effect on the surface soil of greenhouse, and it is linearly correlated with temperature. In terms of crop growth, LCF significantly ($p < 0.05$) increased the photosynthetic rate at heading stage, and finally increased the yield, total soluble sugar and reduction-type Vitamin C by 8.97–39.53%, 9.22–30.14%, and 1.41–21.09%, respectively. In addition, considering the frequent haze weather in North China, the use of LCF can improve air temperature, $CO_2$ concentration, photosynthetically active radiation (PAR), and soil temperature, and it can effectively deal with the challenge of weak light. In conclusion, LCF can improve the facility environment and improve crop yield and quality, indicating that the implementation of LCF has potential benefits in solving crop yield reduction and quality decline in haze weather. In addition, as the main component of LCF, rare earth materials are a new type of clean energy, which can effectively promote the sustainable development of the agricultural ecosystem.

**Keywords:** light conversion films; greenhouse environment; change weather; vegetable growth; sustainable development



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## 1. Introduction

As an energy intensive planting system, plastic greenhouse relies heavily on fossil fuels and intensive use of various energy sources in order to achieve the highest yield and economic benefits, resulting in a large number of greenhouse gas emissions [1]. Greenhouse cultivation technology has developed rapidly, with about 3.64 million hectares of greenhouses worldwide [2]. The internal irradiance in a greenhouse is usually lower than the exterior irradiance [3]. Moreover, in recent years, haze weather has occurred frequently in North China. In order to avoid the problem of crop yield and quality reduction caused by low temperature and weak light weather, farmers usually take measures such as increasing energy input or using light supplement equipment to reduce the impact of haze weather on crops, which greatly improves agricultural production costs and reduces production efficiency. Excessive energy investment will threaten human health and cause serious waste of resources. In addition, excessive energy investment leads to global warming and endangers the environment [4]. In order to promote the sustainable development of agriculture, green environmental protection and sustainable improvement measures should be taken to improve agricultural production efficiency on the basis of reducing production cost.

Haze weather leads to weak light and low temperature. Temperature, as a key determinant in the process of crop growth and development, hinders the growth of crops [5]. In a greenhouse production system based on natural light, haze weather leads to weak light and low temperature, causing serious adverse environment in the greenhouse, resulting in crop reduction and reduced crop quality [6]. Zhou Jie [7] showed that haze weather led to insufficient light reaching facility vegetables, induced the breeding of bacteria in vegetables, seriously affected the high quality and high yield of crops, and reduced the yield of crops by about 35%. According to previous studies, the low light conditions during the growing period hindered the full development of winter wheat [8]. To solve this problem, using supplementary light measures to increase the light and temperature in the greenhouse is one of the most feasible solutions.

The current supply measures can be divided into three main categories: crop field management, artificial light supply, and the use of functional greenhouse film. For crops, field management measures include the direction of border and ridge, the erection mode, and close planting. The research shows that the reasonable plant row spacing can reduce the mutual interference between plants, alleviate the constraints of environmental resources such as light, water, and soil nutrients on plant growth, and is conducive to the high-quality and high-yield of crops [9]. Qiu et al. [10] found that the single plant yield of tomato (*Solanum lycopersicum* L.) decreased significantly with the increase in planting density, and higher planting density had adverse effects on the fruit number and average fruit weight per plant. Therefore, a suitable level of close planting affects the quality and yield of crops. There is no extra cost to optimize field measures, but the improvement effect is limited.

In recent years, artificial lighting technologies have been gradually applied to production. The artificial light source is used to regulate light quality, increase light intensity, and improve the photosynthetic rate of crops to increase quality and yield [11]. It has been found that the use of HPS (High pressure sodium lamp is a kind of high-intensity gas discharge lamp, belonging to the third generation of electric light sources. Its light-emitting tube is made of translucent aluminum oxide tube, and the shell of the lamp is made of hard glass, referred to as HPS.) and LED (Light emitting diode is a commonly used light emitting device, which emits light by combining electrons and holes and is called LED for short.) lighting increased the fresh weight of cucumber (*Cucumis sativus* L.) and tomato (*Solanum lycopersicum* L.) by 3.5–5 times and 7.5–13 times, respectively [12]. Bliznikas et al. [13] showed that fennel (*Foeniculum vulgare Mill.*) and parsley (*Petroselinum crispum (Mill.) Hill*) illuminated with LED red light could enhance the enrichment of vitamin C and carbohydrates. The yield, dry matter, soluble protein, and nitrate content of lettuce (*Lactuca sativa* L. *var. ramosa Hort.*) treated by artificial lighting can be increased by 24.7–35.8%, 36.7–39.7%, 9.24–9.42%, and 6.75–10.75%, respectively [14]. Although artificial lighting is increasingly widely used, problems such as high energy consumption can reduce the production efficiency of crops.

The use of functional thin films can reduce the input of production cost without direct energy consumption. As a type of functional film, LCF adds a light conversion agent (based on polyethylene, polyvinyl chloride, and other greenhouse films) to enhance light conversion function, improve light quality, and improve light transmittance, together aiming to enhance the utilization efficiency of light energy. Compared with other functional films, LCF can convert part of the ultraviolet light in sunlight into plant-usable purple light, and it has a strong warming effect, which is conducive to regulating plant growth and improving fruit quality [15]. The use of functional films can reduce the investment of production cost without directly consuming energy.

Facility agriculture is particularly widespread in China. According to the results of the third national agricultural census, at the end of 2016, the solar greenhouse covers an area of 334,000 hectares, and the plastic greenhouse covers an area of 981,000 hectares (http://www.stats.gov.cn/, accessed on 10 December 2019). Therefore, the selection of high-performance LCF is expected to become the main research direction of facility agriculture. The main component of LCF refers to an agricultural film additive that can convert near-ultraviolet or green light in sunlight into red–orange light and blue–violet light, which can be divided into rare earth inorganic compounds, rare earth organic compounds and fluorescent dyes according to material properties.

At present, the light conversion agents used are mainly rare earth organic compounds. As a group of transition metals, including lanthanides, scandium, and yttrium, rare earths are widely used in phosphors, catalysts, metallurgy, glass, alloys, medical treatment, national defense, and other fields, especially in the field of clean energy [16]. Rare earth materials can also be used in agriculture as light conversion agents because of their unique luminescent properties and good light transmittance [15]. Compared with artificial lighting, LCF greatly reduces the problem of energy consumption and can be reused. As a result, it can contribute to the development of sustainable agricultural systems. Jijiazeng et al. [17] showed that the Vitamin C, soluble sugar and free amino acid of sweet pepper fruit (*Capsicum frutescens* L. (*syn. C. annuum* L.) *var. grossum Bailey.*) under the LCF shed were increased by 31.56%, 14.37%, and 15.94% compared with those under the OF shed. Compared with OF, the aboveground biomass of different varieties of mustard (*Brassica juncea (L.) Czern. et Coss.*), Chinese cabbage (*Brassica rapa var. glabra Regel*), and tender flower stalk cultivated by LCF increased by more than 16.43% [18]. Weibin Wu et al. [19] found that Chinese cabbage (*Brassica rapa var. glabra Regel*) cultivated with LCF could increase soluble protein (9.09%), polyphenols (21.27%), and soluble sugar (19.15%). At present, the research mainly focuses on the impact of LCF on the crop itself; however, the effects of LCF on the crop mainly relate to changes in the environment and soil parameters in the greenhouse. At present, there remains a lack of comprehensive research on the impact of LCF during crop cultivation.

Therefore, the present study applied LCF to two seasons of experimental research on leafy vegetables and conducted a systematic analysis of facility environment, soil, and crop parameters. Leafy vegetables were chosen as the large planting scale in the greenhouse. In addition, the feasibility under the haze weather condition was discussed. The aims and innovative developments of the paper are as follows: (i) This study investigated the effect pathway of LCF used as the light-supplying source; (ii) this study examined the LCF application and considered different kinds of leafy vegetables and different weather conditions; (iii) the current study discussed the cost and energy calculation of different types of lighting methods and to achieve a low carbon production of greenhouse crops, addressing the hazy weather. The findings of this research will contribute to the search for a sustainable and effective method of light supply to improve crop yield under the background of climate change.

## 2. Materials and Methods

### *2.1. Experimental Design*

The experiment was conducted at the National Experiment Station for Precision Agriculture in Changping District, Beijing from September 2019 to April 2020 (Figure 1). Two greenhouses with the same specifications were selected for the experiment. The length of the greenhouses was 40 m, the span was 6.5 m, and the height was 3 m. The greenhouses were covered with the LCF and the OF, of which the conversion film was selected from the single optical film developed by Shandong Shunming Fluorescence Technology Co., LTD., Shangdong, China (LCF, PVC material, thickness 0.12 mm). The ordinary film was selected from the common ordinary film (OF, PO material, thickness 0.12 mm) produced by Shandong Shenghua Plastic Industry Co., LTD., Shangdong, China. The first crop was Italian lettuce (*Lactuca sativa L. Var. ramosa Hort.*), which was planted in the warm room on 18 September 2019 and harvested on 12 November 2019. The second crop was Chinese cabbage, which was planted in the warm room on 10 January 2020 and harvested on 14 April 2020. Except for different coverings of greenhouse film, other facilities and field management were kept the same.

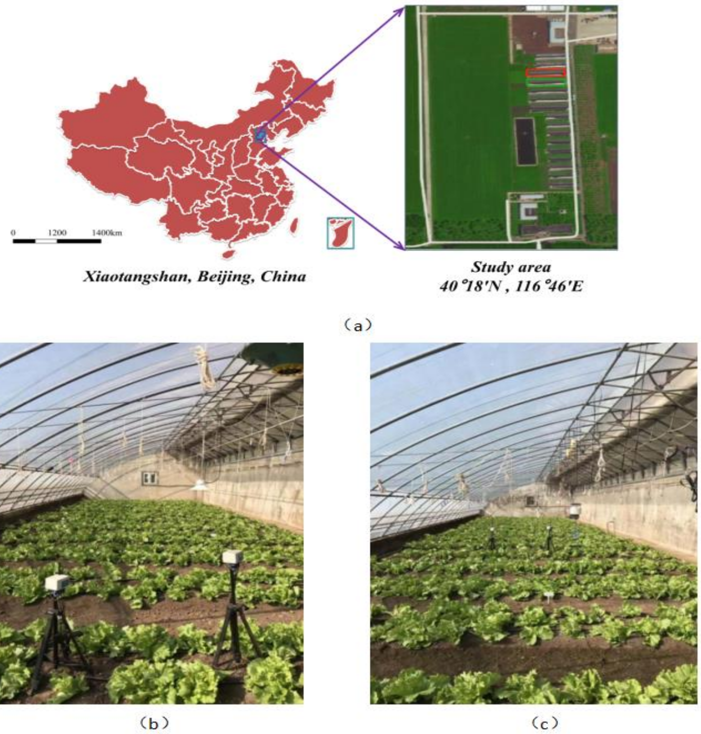


**Figure 1.** Experimental site and layout of the two seasons. (**a**) Location of the study area for the two-season experiment. The green box indicates the light conversion film greenhouse, and the red box indicates the ordinary film greenhouse. Photographs of the light conversion film greenhouse and ordinary film greenhouse are shown in (**b**,**c**), respectively.

Each ridge contained 24 greenhouse-grown crops, with 2 rows per ridge planting. Drip irrigation was applied, with each row crop receiving a drip tape. The head of the drip irrigation system comprised control equipment such as closed bucket, check valve, and gate valve, as well as metering equipment such as a water meter and pressure gauge. The whole drip irrigation system was equipped with two-stage filtration (mesh filter and laminated filter). The operating pressure of the drip irrigation system was 0.1 MPa.

### *2.2. Measurement Indexes*

#### 2.2.1. Determination of Properties of Light Conversion Film

The spectral transmittance and light transmittance of the LCF and the OF used in the test were detected by spectrophotometry. Choose sunny and cloudy morning time (10:00–11:00), respectively, and use spectrometer (AVANTES, AvaSpec-ULS2048XL-EVO-RS-UA, Apeldoom, The Netherlands) to measure the irradiance of LCF and OF.

#### 2.2.2. Greenhouse Environment Monitoring

According to the meteorological station (Beijing Agricultural Intelligent Equipment Technology Research Center, WS100; the accuracy of air temperature, air humidity, and carbon dioxide concentration were ±0.2 °C, ±1.5% RH and ±50 ppm, respectively, and the calibration error of photosynthetic effective radiation is ±5%), the changes of environmental air temperature (°C), air humidity (%), $CO_2$ concentration (mg·L$^{-1}$) and photosynthetically active radiation (PAR, μmol m$^{-2}$s$^{-1}$) were observed.

#### 2.2.3. Determination of Soil Parameters

An EC-5 soil moisture sensor (Decagon, Pullman, WA, USA, Accuracy ± 3% VWC) was used to monitor the change of soil temperature (°C) in real time. Two sets were placed in each greenhouse, respectively, in the middle area of the greenhouse.

#### 2.2.4. Crop Index Determination

The photosynthetic parameters of plants were measured by CIRAS-3 portable photosynthetic analyzer (PP Systems, Amesbury, MA, USA), from 8:00 to 16:00, on a typical sunny and cloudy day during the growth period. The measured items were net photosynthetic rate (Pn), stomatal conductance (Gs), intercellular $CO_2$ concentration (Ci) and transpiration rate (Tr). The measurements were repeated three times for each blade, and the average value was taken for analysis.

Fixed plants were selected for each treatment for yield measurement, and the number of fruits, single fruit weight, single plant yield, and yield per unit area yield were measured several times every five days. After harvest, three fruits were selected from each treatment to test the fruit quality. The total soluble sugar (Anthrone colorimetry), soluble protein (Coomassie brilliant blue staining method), and reduction-type Vitamin C (Spectrophotometry) were then determined.

### *2.3. Data Analysis*

Microsoft Excel 2019 and Origin 2017 software were used to process data and maps, SPSS 22.0 software was used for statistical analysis, one-way ANOVA was used for significance test, and Pearson correlation coefficient was used for correlation analysis ($p < 0.05$, $p < 0.01$).

## 3. Results

### *3.1. Performance Test of Light Conversion Film*

In order to further understand the light conversion effect of the LCF, the spectral transmittance and transmittance of the LCF and the OF used in the test were detected by spectrophotometry (Figure 2a). Through the detection, it is found that the spectral transmittance of the LCF under red–orange light is higher than that of the OF, and the average value of the two kinds of greenhouse film at this wavelength is 88.1% and 86.8%, respectively, the LCF is 1.3% higher than the OF. Under the yellow–green light (500−600 nm), the LCF is lower than the OF, the average calculation is 87.2% and 88.2% respectively, and the LCF is 1% lower than the OF. It can be seen that the LCF converts the yellow−green light (500–600 nm), in visible light, into red–orange light (600–700 nm), thus increasing the proportion of red−orange light (600–700 nm) (1% yellow−green light is converted into 1.3% red−orange light) and promoting the absorption of nitrogen, phosphorus, potassium, and other nutrient elements by crops. In addition, through the test results, it can be seen that there is no significant difference in the effect of the single LCF and the OF on blue−violet light (400–480 nm).

Light transmittance is the prerequisite to ensure the high quality and high yield of protected crops. Therefore, the light transmittance of LCF and OF was tested under visible light conditions (Figure 2b). It was found that the light transmittance of LCF and OF were 87.84% and 79.17% respectively, and the LCF was 8.67% higher than OF. Therefore, LCF has better light transmittance than OF under visible light conditions.

Solar radiation plays an important role in the growth of crops. The greater the intensity of solar radiation, the greater the luminous flux density, the more light quanta supplied, and the greater the intensity of photosynthesis [20]. The irradiance under the LCF and the OF was measured from 10:00 to 11:00 on sunny and cloudy days, respectively (Figure 3). It can be found that, in both sunny and cloudy days, the irradiance of the LCF in the visible band (400−780 nm) is higher than that of the OF, which is as follows: outdoor environment > LCF > OF. Red–orange light and blue–violet light are important light qualities for chlorophyll absorption and photosynthesis during plant growth [21].

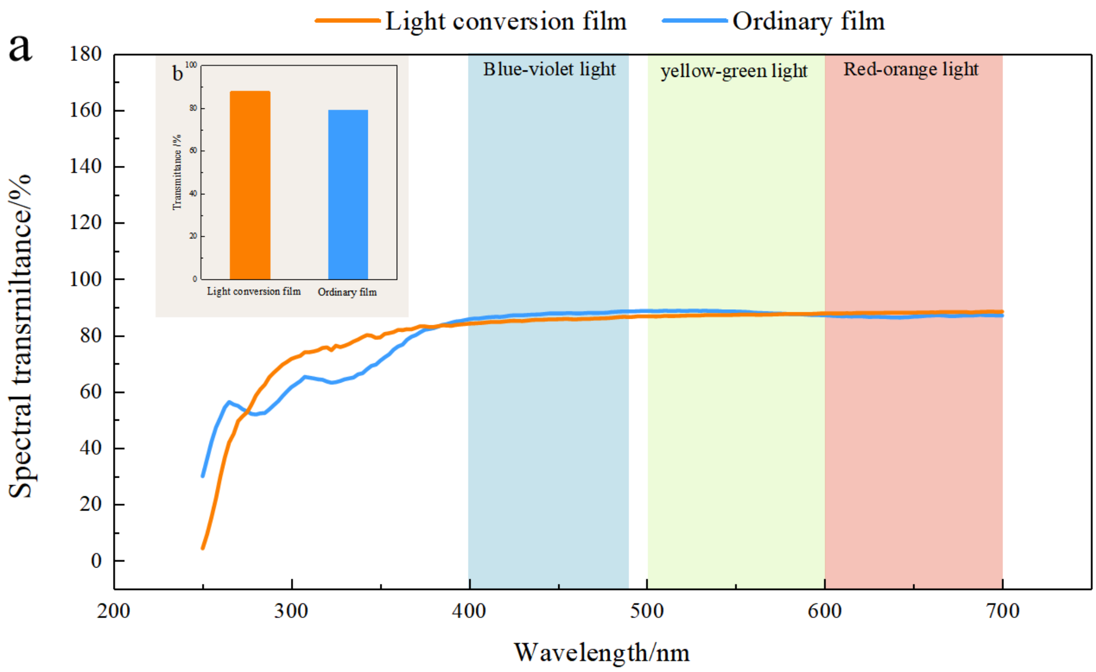


**Figure 2.** Performance test of light conversion film and ordinary film for spectral transmittance and transmittance (**a**) Indicates the performance analysis of the spectral transmittance under the light conversion film and ordinary film; (**b**) Indicates the performance analysis of light transmittance under light conversion film and ordinary film.

Through integral calculation, it is found that in any weather, the intensity of red-orange light and blue−purple light is outdoor environment > LCF > OF, and the radiation intensity in sunny days is higher than that in cloudy days. In sunny days, the red−orange light and blue−violet light of the film are 11.68% and 10.21% higher than that of the OF. In cloudy days, the red−orange light and blue−violet light of the film are 24.17% and 13.90% higher than that of the OF. In cloudy days, the irradiance of the film is higher than that of the sunny day. It can be seen that the use of single LCF can not only effectively improve the conversion of red−orange light but also synchronously enhance the irradiation intensity of red−orange light and blue−violet light.

### *3.2. Effect of Light Conversion Films on the Greenhouse Environment*

#### 3.2.1. Air Temperature

Air temperature is one of the important environmental parameters affecting crop growth. Figure 4a shows the effect of LCF on daily average air temperature in each greenhouse. The average air temperature change trend of LCF and OF was consistent as a whole, but the values varied by film type. During the first crop cultivation period, because of the influence of season, average air temperature in the greenhouse gradually decreased with the advancement of the growth period, but the fluctuation was relatively stable. The average air temperature at LCF is 19.72 °C, the maximum air temperature is 26.42 °C, and the minimum air temperature is 14.83 °C. The air temperature under OF is 19.32 °C, the maximum air temperature is 25.78 °C, and the minimum air temperature is 14.49 °C. The average air temperature under LCF was slightly higher than that under OF in the whole growth period (an average increase of 0.4 °C).

The air temperature in the temperature chamber of the second crop increased slowly with time, and it fluctuated violently compared with the first crop. The average air temperature of LCF and OF were 14.39 °C and 13.48 °C, respectively, and LCF was 6.75% higher than OF. Through significant analysis, a significant difference between LCF and OF in the first crop and a highly significant difference in the second crop is shown.

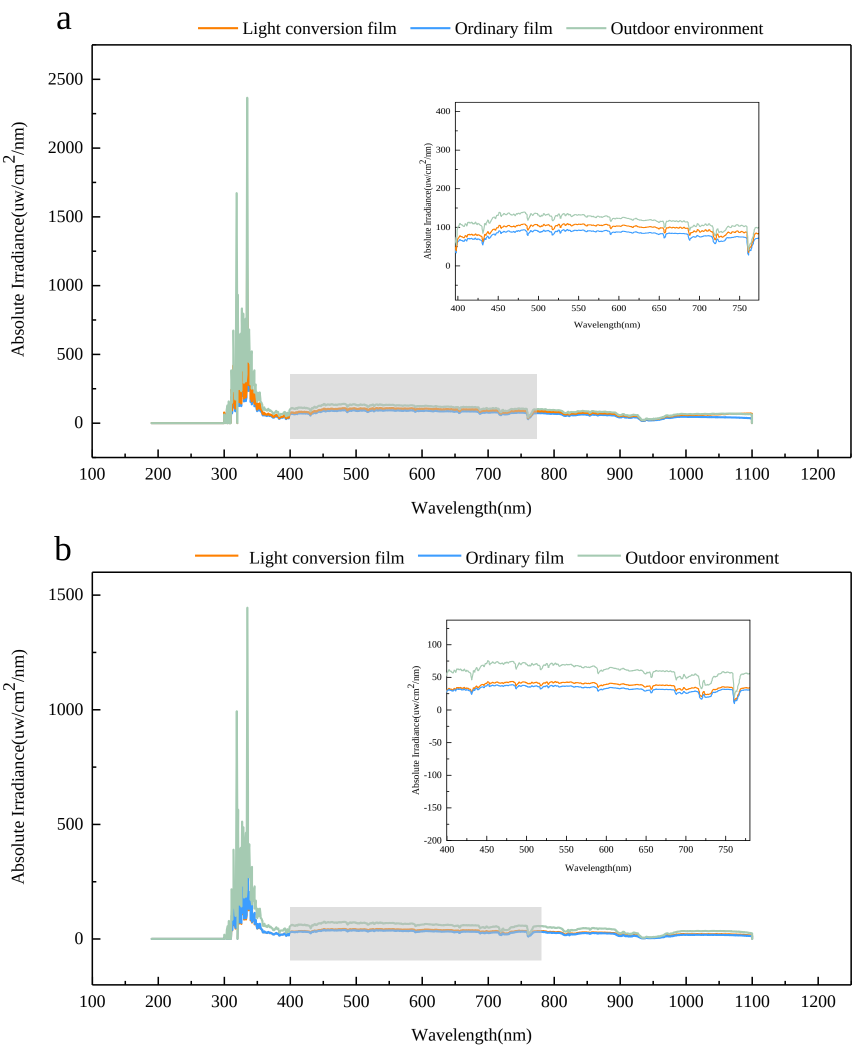


**Figure 3.** Irradiance analysis of light conversion film and ordinary film (**a**) Indicates the comparative analysis of irradiance between light conversion film and ordinary film under sunny days; (**b**) Indicates the comparative analysis of irradiance between light conversion film and ordinary film under cloudy weather.

The effect of LCF on air temperature is shown in Figure 4b. During the first crop, LCF had a consistent enhancing effect on air temperature, but the temperature increase was small at 0−1 °C. During the cultivation period of the second crop, the consistency of air temperature increase range was lower than that of the first crop, but the range of the increase was higher at 0−3 °C. The average growth rates of the first crop in the seedling, rosette, and fruiting stages were 1.88%, 2.54%, and 2.04%, respectively. The growth rates of the second crop in the seedling, rosette, and fruiting stages were 13.22%, 1.92%, and 8.23%, respectively. The single−day maximum temperature variables of the first and second crops were observed in the rosette stage (5.71 °C) and heading stage (12.81 °C), respectively.

Table 1 shows the effect of LCF on greenhouse air temperature under different weather conditions. The air temperature of the greenhouse using LCF was significantly higher than that under OF. For both crops, LCF improved air temperature relative to that under OF in any weather, but the improvement magnitude was different for the two crops. Overall, the improvement degree of air temperature is sunny day > haze day ≥ cloudy day, and the effect of sunny day is better, which increases by 0.20−2.08 °C compared with OF. In cloudy and haze weather, the improvement results were similar, which were 0.19−1.42 °C and 0.14−1.89 °C, respectively.

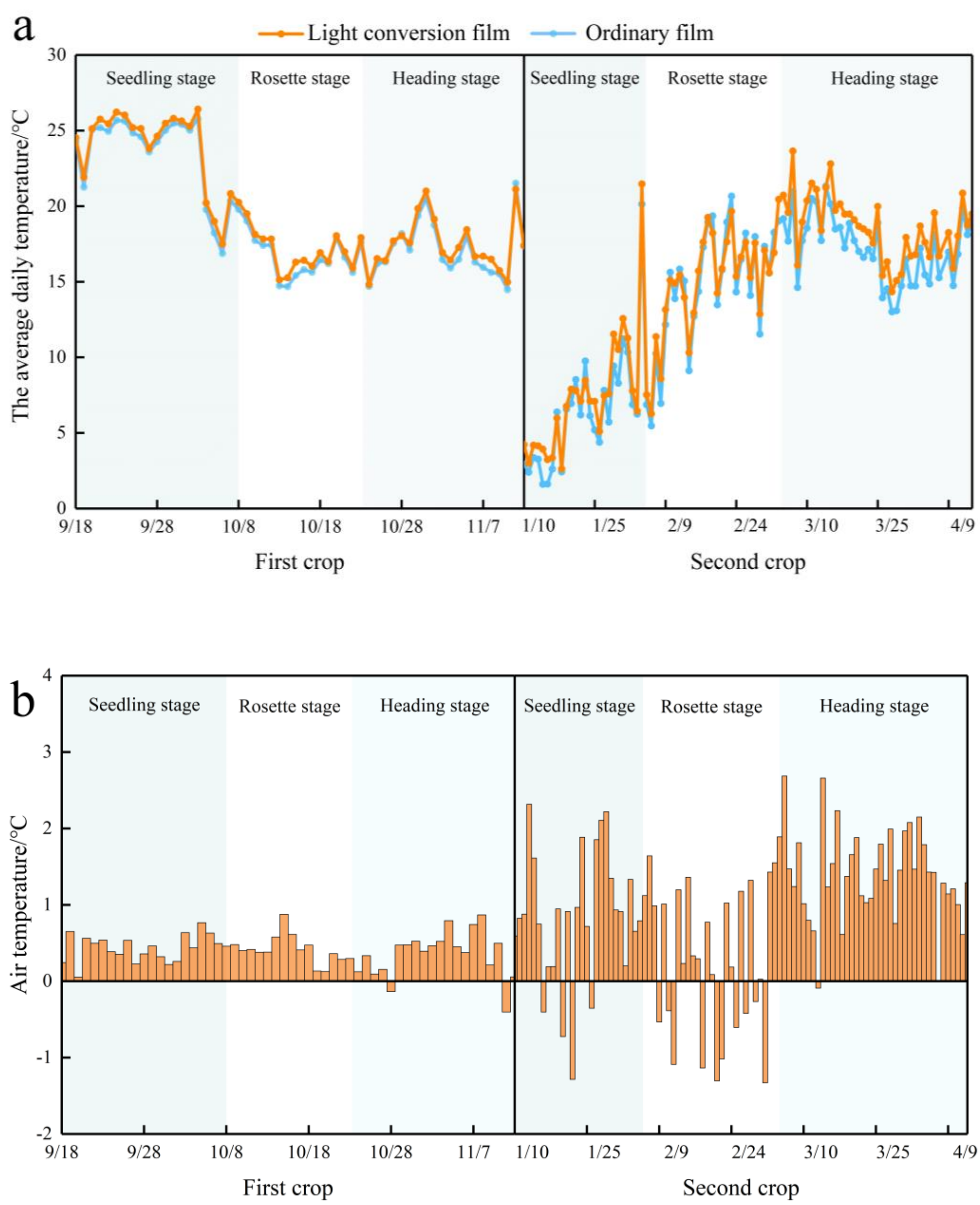


**Figure 4.** Effects of light conversion film (LCF) and ordinary film (OF) on greenhouse air temperature under different crops. (**a**) Indicates the daily average air temperature change in the greenhouse environment under the light conversion film and ordinary film. (**b**) Variable representing the difference between daily average air temperature of light conversion films and ordinary films.

### 3.2.2. Greenhouse Air Humidity

A suitable air humidity directly affects the healthy growth of crops and the prevention and control of diseases and insect pests. Figure 5a shows the effect of LCF on the air humidity during the entire growth period of the crop. Combining the data before and after the two crops reveals that the change trend of average air humidity was the same in the LCF and OF greenhouses; however, average air humidity in the LCF was slightly lower than OF by 0.47−2.83%. Because of the short growth period of the first crop, the change of average air humidity in the LCF was relatively small, and the change area was more concentrated, ranging from 54.60% to 89.82%. The second crop showed considerable variation, ranging from 31.26% to 95.96%, and average air humidity in the greenhouse showed a gradually decreasing trend. Extremely significant ($p < 0.05$) and significant differences ($p < 0.01$) were observed between the two crops.

**Table 1.** Analysis on the effect of different weather on air temperature in light conversion film (LCF) and ordinary film (OF) greenhouse under different crops.

| First Crop | | | | | Second Crop | | | | |
|---|---|---|---|---|---|---|---|---|---|
| **Date** | **Weather Conditions** | **Air Temperature under LCF (°C)** | **Air Temperature under OF (°C)** | **Variable (°C)** | **Date** | **Weather Conditions** | **Air Temperature under LCF (°C)** | **Air Temperature under OF (°C)** | **Variable (°C)** |
| 18 September 2019 | Sunny | 24.54 | 24.29 | +0.25↑ | 10 January 2020 | Sunny | 4.24 | 2.95 | +1.29↑ |
| 05 October 2019 | Sunny | 19.00 | 18.24 | +0.76↑ | 03 February 2020 | Sunny | 6.46 | 6.26 | +0.20↑ |
| 08 October 2019 | Sunny | 20.26 | 19.80 | +0.46↑ | 16 February 2020 | Sunny | 15.73 | 14.36 | +1.37↑ |
| 14 October 2019 | Sunny | 15.27 | 14.69 | +0.58↑ | 13 March 2020 | Sunny | 18.40 | 17.74 | +0.66↑ |
| 07 November 2019 | Sunny | 16.70 | 15.96 | +0.74↑ | 02 April 2020 | Sunny | 16.81 | 14.73 | +2.08↑ |
| 11 October 2019 | Cloudy | 17.83 | 17.42 | +0.41↑ | 24 February 2020 | Cloudy | 15.37 | 14.34 | +1.03↑ |
| 16 October 2019 | Cloudy | 16.43 | 15.81 | +0.62↑ | 25 February 2020 | Cloudy | 16.66 | 16.47 | +0.19↑ |
| 18 October 2019 | Cloudy | 16.93 | 16.46 | +0.47↑ | 09 March 2020 | Cloudy | 18.97 | 17.73 | +1.24↑ |
| 01 November 2019 | Cloudy | 19.15 | 18.76 | +0.39↑ | 24 March 2020 | Cloudy | 17.57 | 16.54 | +1.03↑ |
| 10 November 2019 | Cloudy | 14.99 | 14.49 | +0.50↑ | 07 April 2020 | Cloudy | 16.70 | 15.28 | +1.42↑ |
| 21 September 2019 | Haze | 25.76 | 25.20 | +0.56↑ | 18 January 2020 | Haze | 2.63 | 2.44 | +0.19↑ |
| 26 September 2019 | Haze | 25.14 | 24.61 | +0.53↑ | 11 February 2020 | Haze | 14.91 | 13.89 | +1.02↑ |
| 19 October 2019 | Haze | 16.35 | 16.21 | +0.14↑ | 06 March 2020 | Haze | 19.59 | 17.70 | +1.89↑ |
| 23 October 2019 | Haze | 17.93 | 17.63 | +0.30↑ | 25 March 2020 | Haze | 19.99 | 18.71 | +1.28↑ |
| 09 November 2019 | Haze | 15.75 | 15.53 | +0.22↑ | 14 April 2020 | Haze | 19.50 | 18.94 | +0.56↑ |

Note: "↑" means that the air temperature under the light conversion film environment is higher than that under the ordinary film, and "↓" means that the air temperature under the light conversion film environment is lower than that under the ordinary film.

Figure 5b shows that there was a variable effect of LCF use on greenhouse average air humidity. The average air humidity in the LCF greenhouse, for the first crop, was generally lower than that under OF, with regularity. Compared with the data for the second crop, the consistency reduced, and it was slightly higher than OF in some growth periods, especially in the rosette period. The growth rates of the OF greenhouse for the first crop in the seedling, rosette, and fruiting stages were 4.90%, 2.90%, and 1.12%, respectively. In the OF greenhouse for the second crop, the absolute values of the changes in the seedling, rosette, and fruiting stages were 1.95%, 1.68%, and 1.00%, respectively. During the entire growth period, about 43% of the growth days have a higher rate of average air humidity in the LCF greenhouse than OF.

Table 2 shows the changes of air humidity under different weather conditions. During the cultivation of the first crop, LCF significantly reduced air humidity in the greenhouse, decreasing in the order sunny days > cloudy days > haze days. Compared with the first crop, the uniformity of the air humidity was lower in the second crop. In sunny and haze weather, the air humidity under LCF was slightly higher than that OF, with the highest being 9.3% and 1.73% higher than that of OF. Under cloudy conditions, LCF reduced the air humidity in the greenhouse as a whole, and the average change decreased by 0.71%.

### 3.2.3. Greenhouse $CO_2$ Concentration

As an essential raw material for photosynthesis, $CO_2$ directly affects the growth and development of crops. Figure 6a shows the effect of LCF on the $CO_2$ concentration in the greenhouses. The data for the second set of crops is missing because of a sensor failure. In this study, only the data from 10 January 2020 to 28 February 2020 were selected for analysis. The data for the two crops showed that there was no difference in the trend of the average daily $CO_2$ concentration between LCF and OF, and the $CO_2$ concentration in the LCF greenhouse was significantly higher than that under OF. Moreover, single-factor analysis of variance indicated that there was a highly significant difference ($p < 0.01$) in the $CO_2$ concentration in the LCF and OF greenhouses. For the first crop, as the growth period progresses and the weather gradually became colder, the $CO_2$ concentration gradually increased, but the change was relatively slow. The $CO_2$ concentration of LCF increased by an average of 32% compared with OF. However, the second crop data showed the opposite phenomenon to the first crop. As the growth period and the weather gradually became warmer, the $CO_2$ concentration showed a small decrease, and the frequency of changes was more intense when observing the entire growth period. In addition, the average daily

$CO_2$ concentration in the LCF greenhouse, in the second set of crop data, increased by 30.99% compared with OF. Combining the data of the two crops, it can be seen that the maximum $CO_2$ concentration in the LCF greenhouse occurred in the heading and rosette stages, respectively, which were 17.57−22.73% higher than the values observed for the OF on the same day.

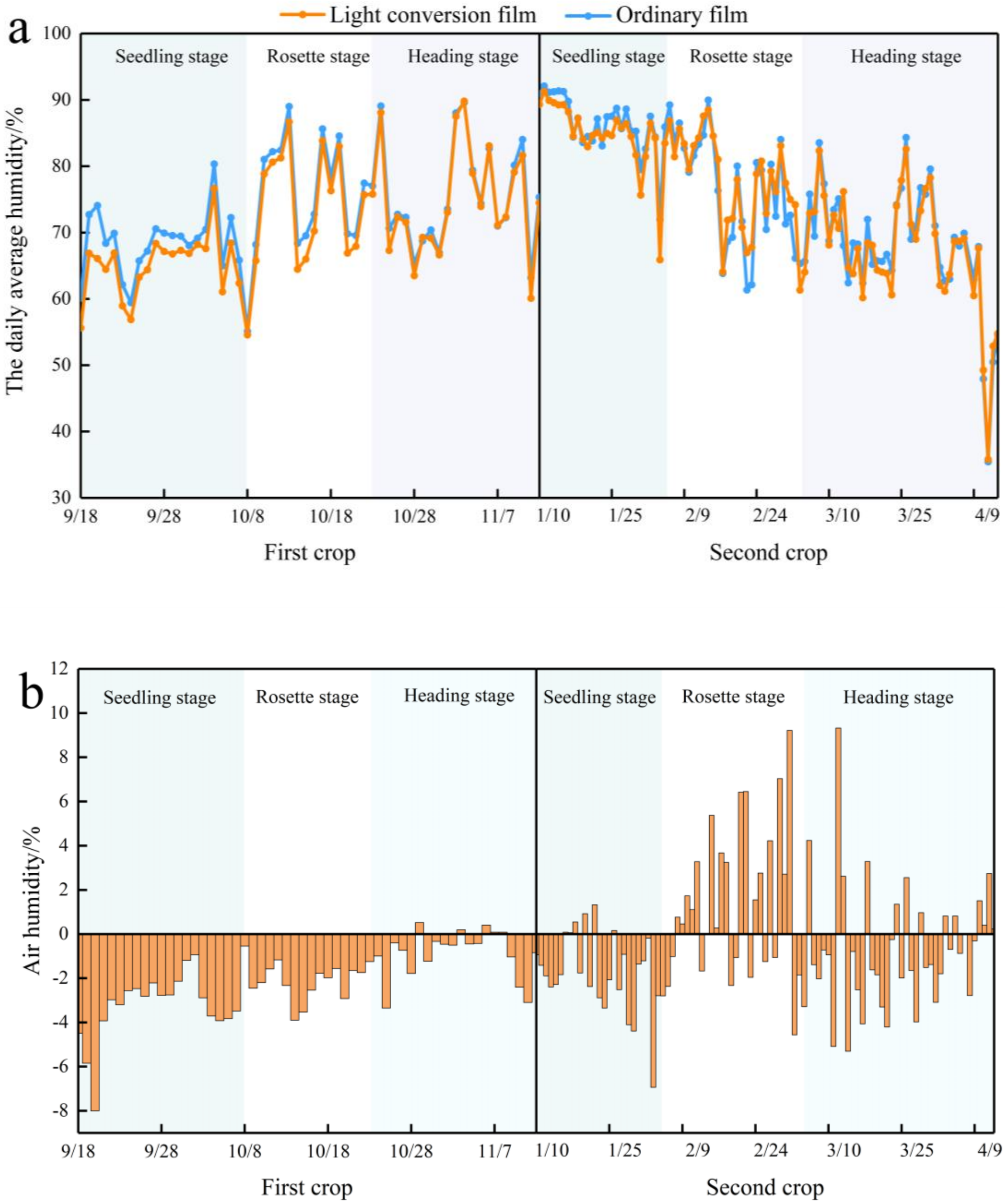


**Figure 5.** Effects of light conversion film (LCF) and ordinary film (OF) on air humidity in greenhouse under different crops. (**a**) Indicates the daily average air humidity change in the greenhouse environment under light conversion film and ordinary film. (**b**) Variable representing the difference between daily average air humidity of light conversion films and ordinary films.

**Table 2.** Analysis of the effect of different weather on air humidity in light conversion film (LCF) and ordinary film (OF) greenhouses under different crops.

| First Crop | | | | | Second Crop | | | | |
|---|---|---|---|---|---|---|---|---|---|
| **Date** | **Weather Conditions** | **Air Humidity under LCF (%)** | **Air Humidity under OF (%)** | **Variable (%)** | **Date** | **Weather Conditions** | **Air Humidity under LCF (%)** | **Air Humidity under OF (%)** | **Variable (%)** |
| 18 September 2019 | Sunny | 55.66 | 60.15 | −4.49↓ | 10 January 2020 | Sunny | 92.81 | 94.59 | −1.78↓ |
| 05 October 2019 | Sunny | 61.10 | 65.02 | −3.92↓ | 03 February 2020 | Sunny | 87.03 | 87.22 | −0.19↓ |
| 08 October 2019 | Sunny | 54.60 | 55.14 | −0.54↓ | 16 February 2020 | Sunny | 83.33 | 77.95 | +5.38↑ |
| 14 October 2019 | Sunny | 64.49 | 68.39 | −3.90↓ | 13 March 2020 | Sunny | 77.80 | 68.47 | +9.33↑ |
| 07 November 2019 | Sunny | 71.11 | 71.02 | +0.09↑ | 02 April 2020 | Sunny | 61.63 | 64.72 | −3.09↓ |
| 11 October 2019 | Cloudy | 80.64 | 82.21 | −1.57↓ | 24 February 2020 | Cloudy | 80.85 | 82.80 | −1.95↓ |
| 16 October 2019 | Cloudy | 70.24 | 72.78 | −2.54↓ | 25 February 2020 | Cloudy | 83.03 | 81.47 | +1.56↑ |
| 18 October 2019 | Cloudy | 76.32 | 78.30 | −1.98↓ | 09 March 2020 | Cloudy | 77.11 | 79.13 | −2.02↓ |
| 01 November 2019 | Cloudy | 73.08 | 73.54 | −0.46↓ | 24 March 2020 | Cloudy | 75.28 | 75.53 | −0.25↓ |
| 10 November 2019 | Cloudy | 81.64 | 84.05 | −2.41↓ | 07 April 2020 | Cloudy | 69.73 | 70.61 | −0.88↓ |
| 21 September 2019 | Haze | 64.48 | 68.40 | −3.92↓ | 18 January 2020 | Haze | 90.46 | 90.39 | +0.07↑ |
| 26 September 2019 | Haze | 64.42 | 67.23 | −2.81↓ | 11 February 2020 | Haze | 85.69 | 83.96 | +1.73↑ |
| 19 October 2019 | Haze | 83.01 | 84.56 | −1.55↓ | 06 March 2020 | Haze | 74.06 | 77.35 | −3.29↓ |
| 23 October 2019 | Haze | 75.80 | 77.05 | −1.25↓ | 25 March 2020 | Haze | 79.72 | 78.37 | +1.35↑ |
| 09 November 2019 | Haze | 79.13 | 80.16 | −1.03↓ | 14 April 2020 | Haze | 53.33 | 53.09 | +0.24↑ |

Note: "↑" means that the air humidity under the light conversion film environment is higher than that under the ordinary film, and "↓" means that the air humidity under the light conversion film environment is lower than that under the ordinary film.

Figure 6b shows the effect of LCF on the $CO_2$ concentration variables in the greenhouse. The data for both crops show that the $CO_2$ concentration in the LCF greenhouse was significantly higher than that in the OF greenhouse and had a higher consistency. In the first crop, the $CO_2$ concentration gradually increased over time, and that of the second crop was low in the late seedling stage and then increased, again, in the rosette stage. The average value of the $CO_2$ concentration variation in the two crops reached 32.26% and 31.98%, respectively. The maximum values of the variables in the two crops were 263.83 and 487.03 mg·L−1, respectively.

Table 3 shows the $CO_2$ concentration in the LCF greenhouse under different weather conditions. These data indicate that LCF had a significant improvement effect on the $CO_2$ concentration in the greenhouse, but the improvement effect was different according to different weather conditions. In the first crop, the increase is most obvious in sunny days, which can reach 205.25 mg $L^{-1}$, while reaching 234.83 mg $L^{-1}$ in cloudy days and 192.18 mg $L^{-1}$ in haze days. In the second crop, the concentration and increase in $CO_2$ are slightly different, which is sunny day > haze day > cloudy day, and the highest is 396.31 mg $L^{-1}$, 389.66 mg $L^{-1}$ and 350.76 mg $L^{-1}$, respectively.

### 3.2.4. Photosynthetically Active Radiation

Photosynthetically active radiation (PAR) is an important energy source for the photosynthesis of plants, which directly affects the yield and quality of crops. In this paper, 14 days were selected in the heading period of the two crops to conduct a comparative study of PAR. One-way analysis of variance revealed extremely significant differences between the two crops in the LCF and OF greenhouses. Figure 7 shows that the changes in PAR in LCF and OF greenhouses were very similar, and the PAR in LCF was higher than that in OF. For the first crop, the PAR under LCF could reach 316.46 $\mu molm^{-2}s^{-1}$, and 262.44 $\mu molm^{-2}s^{-1}$ was reached under OF in the same period (17.07% lower than LCF). The data in the selected time period of the second crop show that the maximum PAR in the LCF greenhouse (476.28 $\mu molm^{-2}s^{-1}$) occurred on 3 April 2020, and OF was 41.61 $\mu molm^{-2}s^{-1}$ on the same day (LCF increased by 1044.63% compared with OF). According to the calculation, the daily average PAR under LCF can reach 205.61 and 391.70 $\mu molm^{-2}s^{-1}$ for the two crops, respectively, representing an increase by 24.54% and 42.48%, respectively, compared with OF.

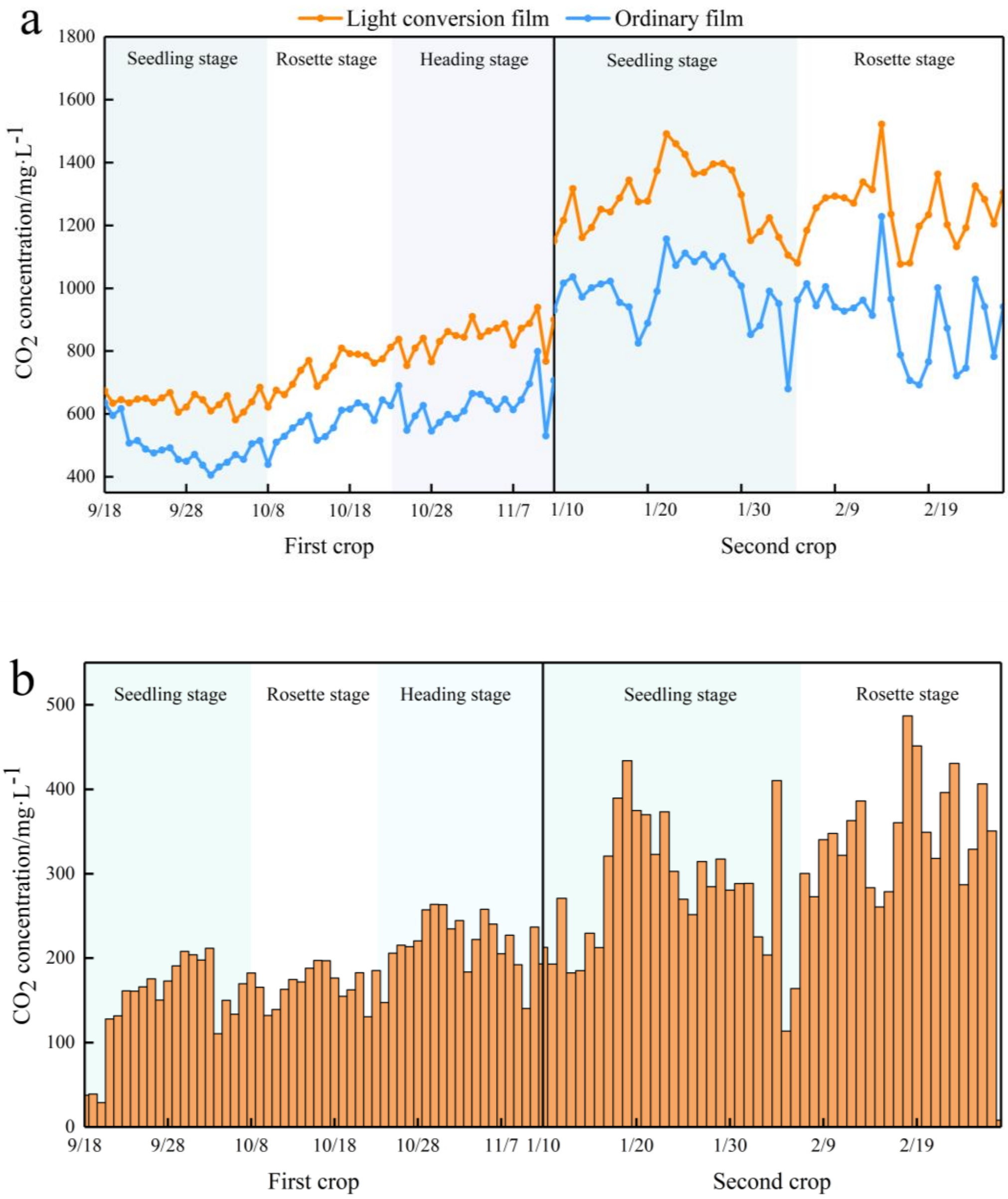


**Figure 6.** Effects of light conversion film (LCF) and ordinary film (OF) on $CO_2$ concentration in greenhouse under different crops. (**a**) Indicates the daily average $CO_2$ concentration change in the greenhouse environment under light conversion film and ordinary film. (**b**) Variable representing the difference between daily average $CO_2$ concentration of light conversion films and ordinary films.

In order to deeply explore the PAR intensity under the two kinds of greenhouse films, the PAR was monitored hourly in sunny days, cloudy days, and haze days during the heading period of the two crops (Figure 8). It was found that, in the two crops, the PAR intensity under LCF greenhouse film was higher than that under OF greenhouse film in sunny, cloudy, and haze days. It can be seen from the figure that, during the monitoring of two crops, the time of PAR monitored under the two kinds of greenhouse film is highly consistent. Through the change trend of PAR, it is found that the PAR intensity in different weather shows sunny days > cloudy days > haze days. Among them, in the first crop, the maximum PAR of LCF greenhouse film in sunny days, cloudy days and haze days are 67.35, 62.46, and 42.04 μmolm$^{-2}$s$^{-1}$, respectively, and the PAR of OF, at the same time, are 51.9, 45.7, and 32.41 μmolm$^{-2}$s$^{-1}$, respectively. In the second crop, the maximum PAR of LCF under greenhouse film in sunny days, cloudy days, and haze days were 90.83, 80.04, and 76.68 μmol $m^{-2}s^{-1}$, respectively. At the same time, the PAR OF were 73.43, 64.05, and 52.76 $μmolm^{-2}s^{-1}$, respectively.

**Table 3.** Analysis of the effect of different weather on $CO_2$ concentration in light conversion film (LCF) and ordinary film (OF) greenhouse under different crops.

| First Crop | | | | | Second Crop | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Date | Weather Conditions | $CO_2$ Concentration under LCF ($mg·L^{-1}$) | $CO_2$ Concentration under OF ($mg·L^{-1}$) | Variable ($mg·L^{-1}$) | Date | Weather Conditions | $CO_2$ Concentration under LCF ($mg·L^{-1}$) | $CO_2$ Concentration under OF ($mg·L^{-1}$) | Variable ($mg·L^{-1}$) |
| 18 September 2019 | Sunny | 673.92 | 636.17 | +37.75↑ | 10 January 2020 | Sunny | 1173.63 | 960.79 | +212.84↑ |
| 05 October 2019 | Sunny | 606.46 | 456.46 | +150.00↑ | 20 January 2020 | Sunny | 1295.92 | 921.05 | +374.87↑ |
| 08 October 2019 | Sunny | 622.58 | 440.17 | +182.41↑ | 03 February 2020 | Sunny | 1184.79 | 981.00 | +203.79↑ |
| 14 October 2019 | Sunny | 688.75 | 516.88 | +171.87↑ | 17 February 2020 | Sunny | 1105.50 | 744.94 | +360.56↑ |
| 07 November 2019 | Sunny | 819.42 | 614.17 | +205.25↑ | 22 February 2020 | Sunny | 1155.67 | 759.36 | +396.31↑ |
| 11 October 2019 | Cloudy | 695.29 | 556.17 | +139.12↑ | 11 January 2020 | Cloudy | 1236.88 | 1043.89 | +192.99↑ |
| 16 October 2019 | Cloudy | 754.21 | 556.92 | +197.29↑ | 17 January 2020 | Cloudy | 1305.38 | 984.46 | +320.92↑ |
| 18 October 2019 | Cloudy | 792.52 | 616.09 | +176.43↑ | 24 February 2020 | Cloudy | 1438.92 | 1136.06 | +302.86↑ |
| 01 November 2019 | Cloudy | 845.21 | 610.38 | +234.83↑ | 25 February 2020 | Cloudy | 1300.96 | 971.77 | +329.19↑ |
| 10 November 2019 | Cloudy | 939.75 | 799.33 | +140.42↑ | 27 February 2020 | Cloudy | 1321.96 | 971.20 | +350.76↑ |
| 21 September 2019 | Haze | 635.92 | 507.88 | +128.04↑ | 18 January 2020 | Haze | 1360.33 | 970.67 | +389.66↑ |
| 26 September 2019 | Haze | 668.46 | 492.92 | +175.54↑ | 26 January 2020 | Haze | 1383.79 | 1132.10 | +251.69↑ |
| 19 October 2019 | Haze | 790.42 | 635.67 | +154.75↑ | 27 January 2020 | Haze | 1409.29 | 1094.71 | +314.58↑ |
| 23 October 2019 | Haze | 812.52 | 627.22 | +185.30↑ | 28 January 2020 | Haze | 1411.00 | 1126.17 | +284.83↑ |
| 09 November 2019 | Haze | 888.73 | 696.55 | +192.18↑ | 13 February 2020 | Haze | 1331.17 | 944.83 | +386.34↑ |

Note: "↑" means that the $CO_2$ concentration under the light conversion film environment is higher than that under the ordinary film, and "↓" means that the $CO_2$ concentration under the light conversion film environment is lower than that under the ordinary film.

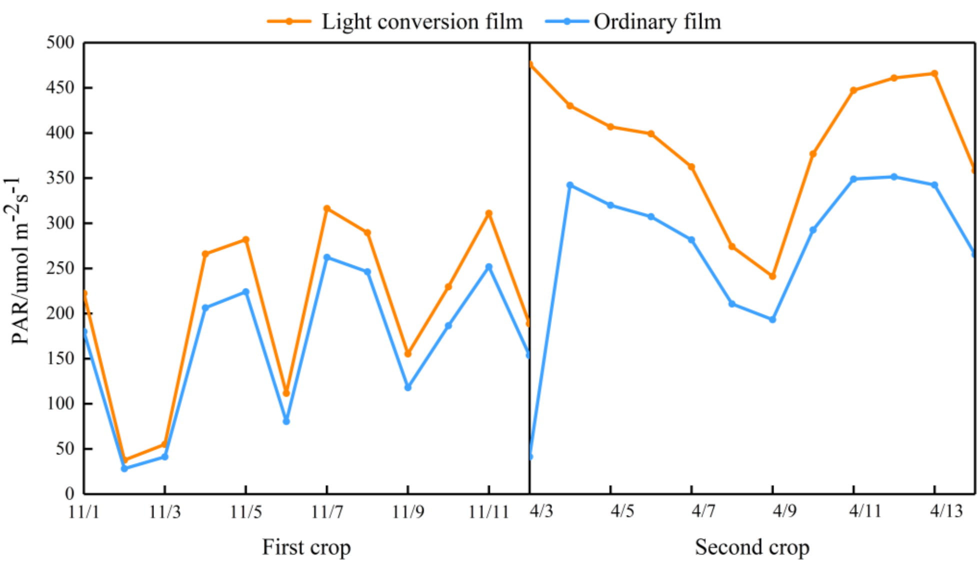


**Figure 7.** Analysis on the effect of light conversion film (LCF) and ordinary film (OF) on Photosynthetic effective radiation under different crops.

The impacts of LCF and OF greenhouse on PAR, under different weather conditions, are shown in Table 4. The PAR of LCF in haze weather is 37.30−92.87 $μmolm^{-2}s^{-1}$ higher than that in OF, which is higher than that in other weather. In the first crop, the improvement effect on sunny days was slightly higher than that on cloudy days, with the highest values of 59.66 $μmolm^{-2}s^{-1}$ and 43.05 $μmolm^{-2}s^{-1}$, respectively. In the second crop, the radiation intensity of PAR is slightly different in the order of sunny days > haze days > cloudy days, with the highest values of 98.17 $μmolm^{-2}s^{-1}$, 92.87 μmol $m^{-2}s^{-1}$, and 84.22 $μmolm^{-2}s^{-1}$, respectively.

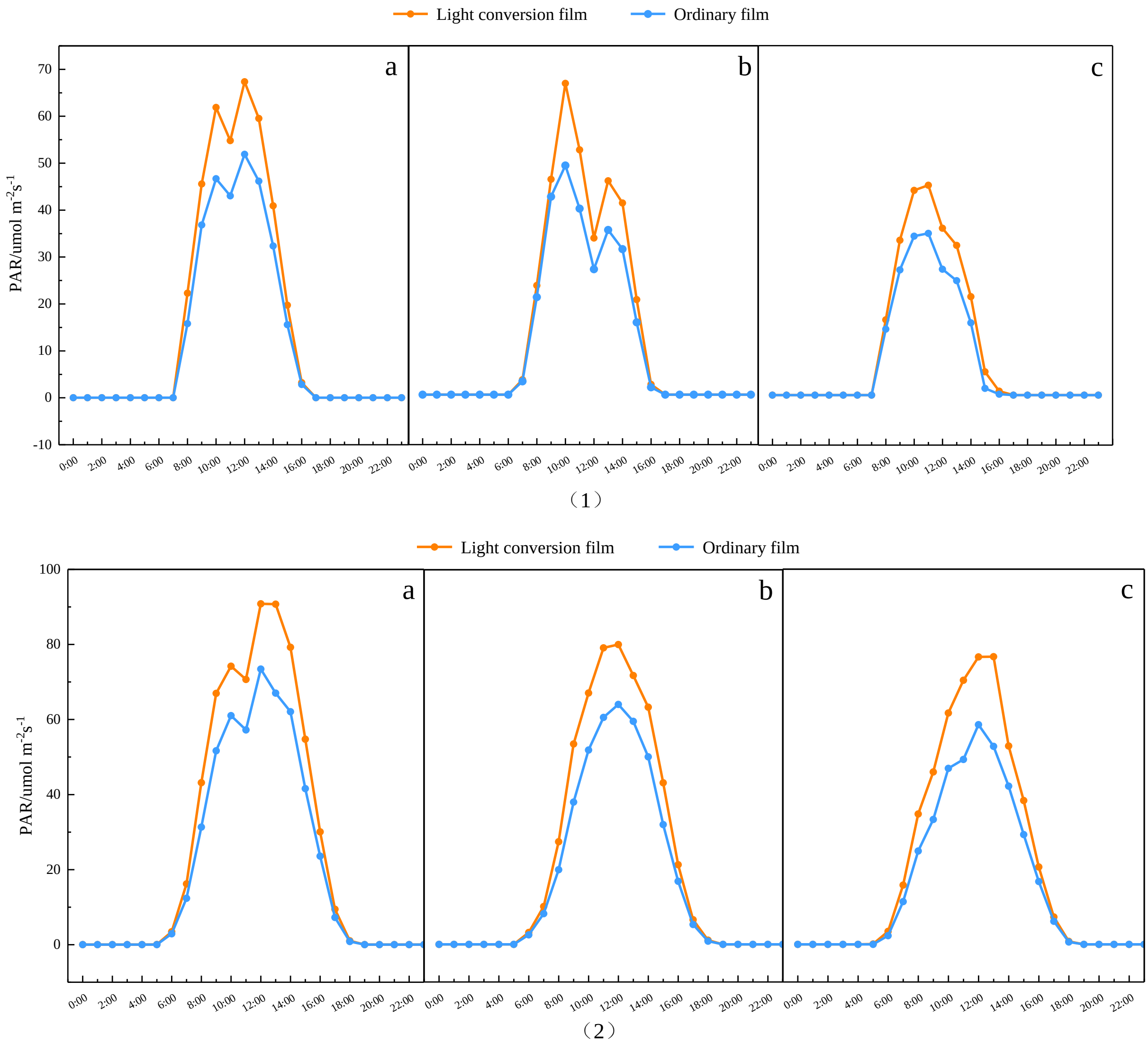


**Figure 8.** Effect of different crops and different weather on hourly photosynthetic effective radiation of light conversion film (LCF) and ordinary film (OF). (**1**) indicates the impact of LCF and OF on PAR in the first crop, and (**2**) indicates the impact of LCF and OF on PAR in the second crop ((**a**) indicates sunny weather; (**b**) indicates cloudy weather; (**c**) indicates haze weather).

**Table 4.** Effects of different crops and different weather on photosynthetic effective radiation under light conversion film (LCF) and ordinary film (OF) greenhouse.

| First Crop | | | | | Second Crop | | | | |
|---|---|---|---|---|---|---|---|---|---|
| **Date** | **Weather Conditions** | **PAR under LCF (µmol $m^{-2}s^{-1}$)** | **PAR under OF (µmol $m^{-2}s^{-1}$)** | **Variable (µmol $m^{-2}s^{-1}$)** | **Date** | **Weather Conditions** | **PAR under LCF (µmol $m^{-2}s^{-1}$)** | **PAR under OF (µmol $m^{-2}s^{-1}$)** | **Variable (µmol $m^{-2}s^{-1}$)** |
| 04 November 2019 | Sunny | 266.16 | 206.50 | +59.66↑ | 05 April 2020 | Sunny | 406.85 | 320.06 | +86.79↑ |
| 07 November 2019 | Sunny | 316.46 | 262.44 | +54.02↑ | 11 April 2020 | Sunny | 447.26 | 349.09 | +98.17↑ |
| 11 November 2019 | Sunny | 311.16 | 251.90 | +59.26↑ | 06 April 2020 | Sunny | 399.25 | 307.36 | +91.89↑ |
| 01 November 2019 | Cloudy | 222.48 | 180.23 | +42.25↑ | 08 April 2020 | Cloudy | 274.35 | 210.86 | +63.49↑ |
| 10 November 2019 | Cloudy | 229.73 | 186.68 | +43.05↑ | 10 April 2020 | Cloudy | 376.96 | 292.74 | +84.22↑ |
| 12 November 2019 | Cloudy | 189.02 | 153.91 | +35.11↑ | 04 April 2020 | Haze | 430.14 | 342.37 | +87.77↑ |
| 09 November 2019 | Haze | 155.53 | 118.23 | +37.30↑ | 07 April 2020 | Haze | 362.66 | 281.74 | +80.92↑ |
| | | | | | 14 April 2020 | Haze | 358.37 | 265.50 | +92.87↑ |

Note: "↑" indicates that PAR under light conversion film environment is higher than that under ordinary film, and "↓" indicates that PAR under light conversion film environment is lower than that under ordinary film.

### 3.3. Effect of Light Conversion Films on the Greenhouse Soil Environment

A suitable soil temperature is conducive to the growth and development of crops. Figure 9 shows the impact of LCF on soil temperature in the two greenhouses. There was no significant difference between LCF and soil temperature in the OF greenhouse. The use of LCF will not provoke large−scale change in the overall changes of temperature in the soil environment, but the values were slightly different between the greenhouses (Figure 9a). In the first crop, soil temperature decreased gradually with the advance of the growth period and the change of the external climate environment. Compared with OF, the average soil temperature under LCF increased by 3.23%. In the second crop, soil temperature fluctuated violently, reaching maximum in the early rosette stage and then decreasing. The maximum soil temperature under LCF was 24.25 °C, which is 1 °C higher than OF on the same day. In the second crop, the average soil temperature of LCF increased by 0.61 °C and 3.82% compared with OF.

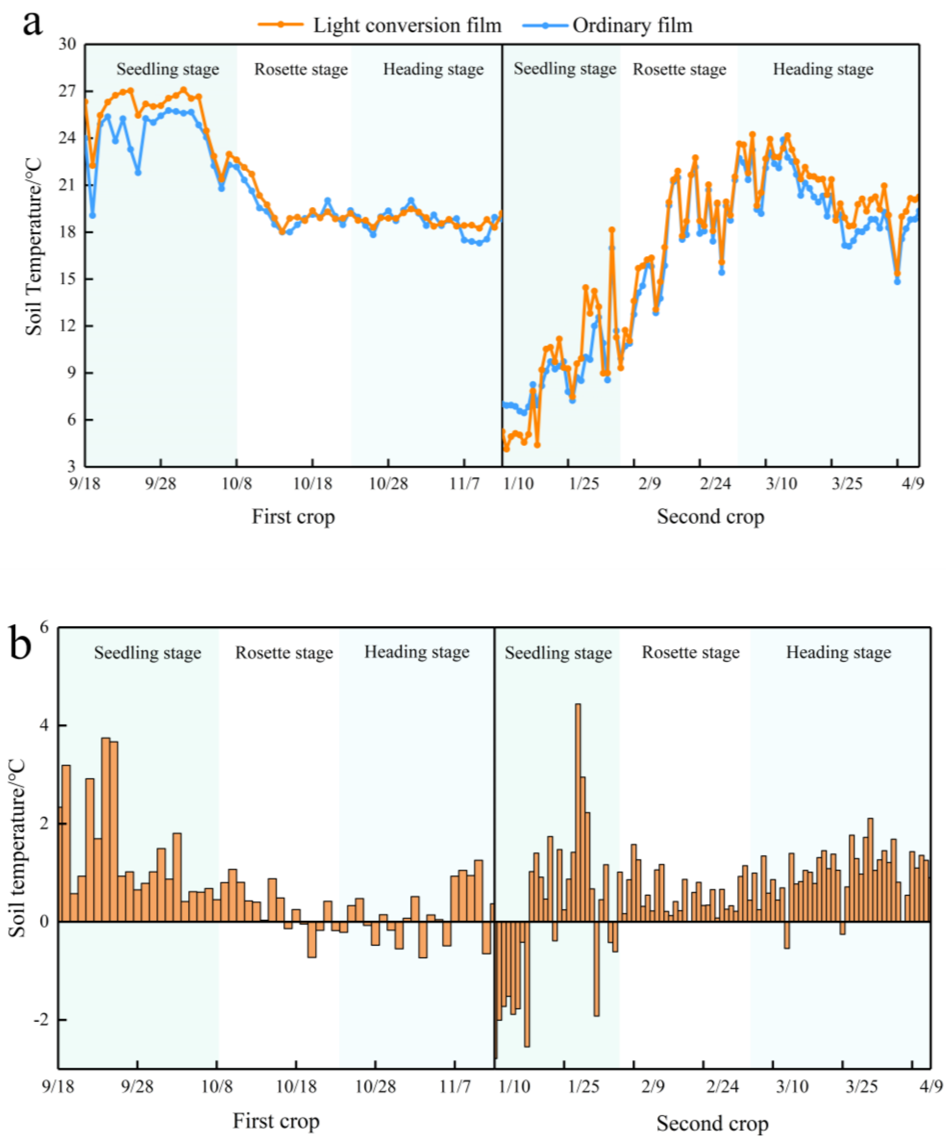


**Figure 9.** Effects of light conversion film (LCF) and ordinary film (OF) on soil temperature in greenhouse under different crops. (**a**) Indicates the daily average soil temperature change in the greenhouse environment under light conversion film and ordinary film. (**b**) Variable representing the difference between daily average soil temperature of light conversion films and ordinary films.

Figure 9b shows soil temperature variables in the LCF greenhouse and reveals that soil temperature was higher than OF throughout most of the growth period. The maximum soil temperature variables of the two crops appeared at the seedling stage, which were 3.75 °C and 4.44 °C, respectively. The soil temperature in the LCF greenhouse increased by 16.10% and 44.31% compared with OF data for the same day. In the first crop, compared with OF, the soil temperature increase in LCF in the seedling, rosette, and fruiting stages were 6.02%, 1.46%, and 0.81%, respectively. The warming trend showed seedling stage > rosette stage > heading stage. In contrast, the second crop soil temperature decreased in the order heading stage > rosette stage > seedling stage, and the growth rates of each stage were 5.11%, 3.17%, and 0.89%, respectively.

The impact of LCF on soil temperature was analyzed according to different weather conditions (Table 5). The soil temperature of LCF greenhouse under different weather conditions is 0.03−2.34 °C higher than that OF greenhouse. In the first crop, the maximum difference of soil temperature, under LCF and OF, is sunny day > cloudy day > haze day, and its values are 2.34 °C, 1.26 °C, and 1.02 °C, respectively. In the second crop, the maximum difference of soil temperature, under LCF and OF, was cloudy days > haze days > sunny days, and the specific values were 1.39 °C, 1.27 °C, and 1.17 °C, respectively.

**Table 5.** Analysis on the effect of different weather on soil temperature, in light conversion film (LCF) and ordinary film (OF) greenhouses, under different crops.

| First crop | | | | | Second crop | | | | |
|---|---|---|---|---|---|---|---|---|---|
| **Date** | **Weather Conditions** | **Soil Temperature under LCF (°C)** | **Soil Temperature under OF (°C)** | **Variable (°C)** | **Date** | **Weather Conditions** | **Soil Temperature under LCF (°C)** | **Soil Temperature under OF (°C)** | **Variable (°C)** |
| 18 September 2019 | Sunny | 26.34 | 24.00 | +2.34↑ | 03 February 2020 | Sunny | 9.01 | 8.56 | +0.45↑ |
| 05 October 2019 | Sunny | 22.86 | 22.25 | +0.61↑ | 04 February 2020 | Sunny | 18.16 | 16.99 | +1.17↑ |
| 08 October 2019 | Sunny | 22.62 | 22.17 | +0.45↑ | 16 February 2020 | Sunny | 17.04 | 15.87 | +1.17↑ |
| 14 October 2019 | Sunny | 18.04 | 18.01 | +0.03↑ | 13 March 2020 | Sunny | 22.80 | 22.11 | +0.69↑ |
| 07 November 2019 | Sunny | 18.44 | 17.50 | +0.94↑ | 02 April 2020 | Sunny | 19.35 | 18.29 | +1.06↑ |
| 11 October 2019 | Cloudy | 20.35 | 19.55 | +0.80↑ | 24 February 2020 | Cloudy | 18.73 | 17.92 | +0.81↑ |
| 16 October 2019 | Cloudy | 18.97 | 18.48 | +0.49↑ | 25 February 2020 | Cloudy | 18.41 | 18.08 | +0.33↑ |
| 18 October 2019 | Cloudy | 19.39 | 19.14 | +0.25↑ | 09 March 2020 | Cloudy | 20.53 | 19.19 | +1.34↑ |
| 01 November 2019 | Cloudy | 19.29 | 19.22 | +0.07↑ | 24 March 2020 | Cloudy | 20.41 | 19.02 | +1.39↑ |
| 10 November 2019 | Cloudy | 18.82 | 17.56 | +1.26↑ | 07 April 2020 | Cloudy | 19.10 | 18.29 | +0.81↑ |
| 21 September 2019 | Haze | 26.31 | 25.38 | +0.93↑ | 26 January 2020 | Haze | 7.50 | 7.25 | +0.25↑ |
| 26 September 2019 | Haze | 26.20 | 25.27 | +0.93↑ | 11 February 2020 | Haze | 15.85 | 14.58 | +1.27↑ |
| 28 September 2019 | Haze | 26.09 | 25.44 | +0.65↑ | 06 March 2020 | Haze | 21.79 | 21.35 | +0.44↑ |
| 30 September 2019 | Haze | 26.74 | 25.72 | +1.02↑ | 25 March 2020 | Haze | 21.38 | 20.33 | +1.05↑ |
| 09 November 2019 | Haze | 18.25 | 17.31 | +0.94↑ | 14 April 2020 | Haze | 20.27 | 19.37 | +0.90↑ |

Note: "↑" means that the soil temperature under the light conversion film environment is higher than that under the ordinary film, and "↓" means that the soil temperature under the light conversion film environment is lower than that under the ordinary film.

### 3.4. Analysis of the Synergistic Influence of Light Conversion Films on Greenhouse Environmental Parameters

Figure 10 presents an analysis of the synergistic effect of LCF on the concentration of air temperature, air humidity, $CO_2$, and soil temperature. The use of LCF did not change the overall distribution of the greenhouse environment, but a significant improvement was observed compared with OF. The improvement effect of stubble was slightly different, and the improvement effect of $CO_2$ concentration was greatest (Figure 10c).

Compared with OF, the monthly average air temperature in the LCF greenhouse was slightly higher (Figure 10a), especially in the second crop, which was 2.22−7.26% higher than OF. The use of LCF increased the air humidity in the greenhouse, so it was lower than OF (Figure 10b). Combining the data for the two crops reveals that, except for the second crop in February, the average air humidity in the LCF greenhouse was consistently lower than that in the OF greenhouse. Figure 10c clearly shows that LCF had a strong effect on increasing the concentration of $CO_2$, and the increased range reached 26.40−34.71%. The increase in air temperature directly affected the increase in soil temperature in the greenhouse (Figure 10d). The soil temperature in the LCF greenhouse was significantly higher than that in the OF greenhouse. This effect was most obvious in September, for the first crop, and in March and April, for the second crop, which were, respectively, 7.48%, 4.12%, and 6.85% higher than the soil temperature in the OF greenhouse at the same time. Analysis of variance was used to test the significance of the above data and revealed a very significant difference between LCF and OF for both crops ($p < 0.01$).

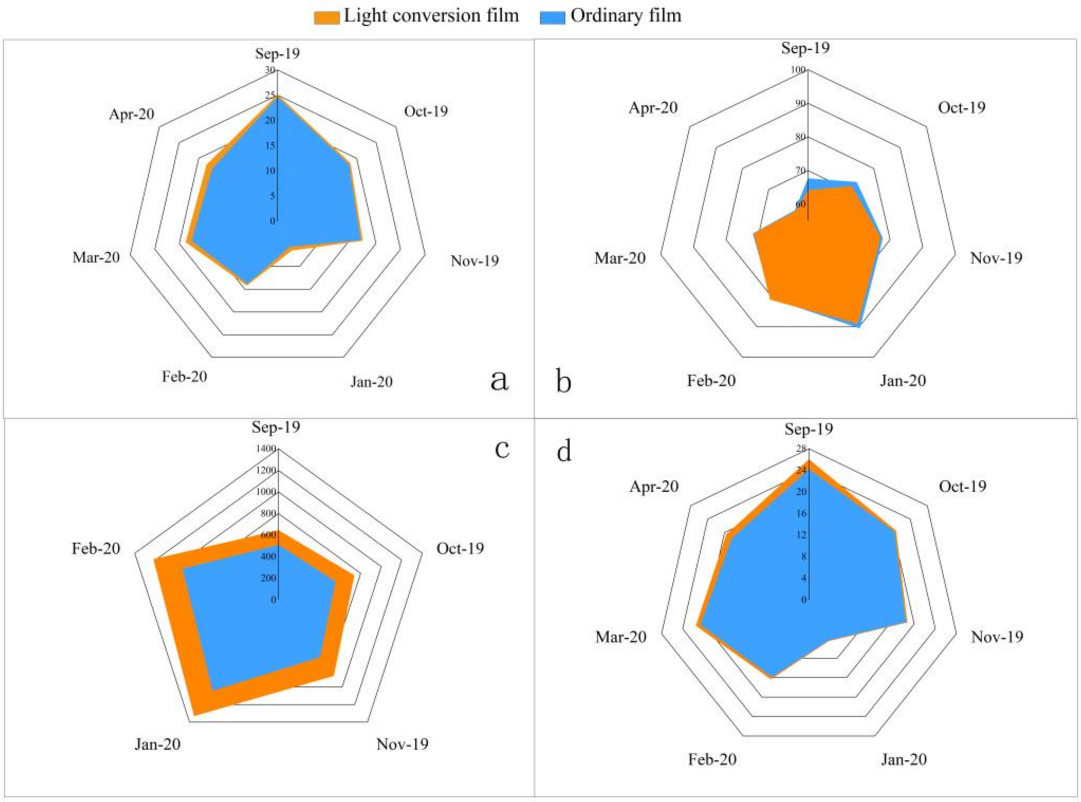


**Figure 10.** Synergistic effects of light conversion film (LCF) and ordinary film (OF) on (**a**) air temperature, (**b**) air humidity, (**c**) $CO_2$ concentration, and (**d**) soil temperature.

## *3.5. Effect of LCF on Crop Growth*

### 3.5.1. Photosynthetic Characteristics of Plant Leaves

To study the effect of LCF on plant growth, photosynthetic parameters of plants in the greenhouse were measured at different time periods during the different growth periods (Figure 11, Table 6). The use of LCF did not change the changes in photosynthesis in plant leaves, which was consistent with OF. Among them, Pn and Ci showed a single peak curve according to the monitored data. Pn showed a gradual downward trend after 12:00, whereas Ci showed an upward trend. The E fluctuated, increased briefly at 12:00 and then decreased. The Gs remained in a relatively consistent state, with no significant change trend. The change rates of Pn, Ci, and Gs were higher in the heading stage than in the rosette stage.

Figure 11a shows the effect of LCF use on Pn. It was found that Pn was higher under LCF than under OF in the heading period, and the highest point occurred at 12:00, which was 46.77% higher than OF in the same period. In contrast, in the rosette stage, Pn at 12:00 was higher than that of LCF. There was no significant difference between LCF and OF in two different growth stages. Figure 11b shows that the overall effect of LCF on Tr, relative to OF, was the same at different growth stages, but the specific values were different. At the heading stage, Tr was significantly higher than that at rosette stage. There was no significant relationship between LCF and OF. Figure 11c shows the effect of LCF on Ci. Regardless of period, the overall change of LCF and OF remained the same. Under LCF, there was a significant difference in Ci between the heading stage and the rosette stage. In addition, there was a significant difference between LCF and OF on the efficiency of Ci in the heading stage. In the later stages, Ci under OF was higher than LCF, and Ci under OF was higher than LCF in the morning in the rosette stage. The highest Ci under LCF, in different periods, occurred at 16:00, which was 2.91−9.73% lower than that under OF in the same period. Figure 11d shows that the Gs of the greenhouses changed slowly after 12:00, whether at rosette stage or heading stage. Under LCF, the Gs in the heading stage was significantly higher than that in the rosette stage. Before 12:00, the Gs under OF was higher at the rosette stage, followed by LCF at the heading stage. In different periods, the highest point for LCF was 2.05−6.48 times higher than that for OF. There was a significant difference between LCF and OF in the effect of Gs in the heading stage.

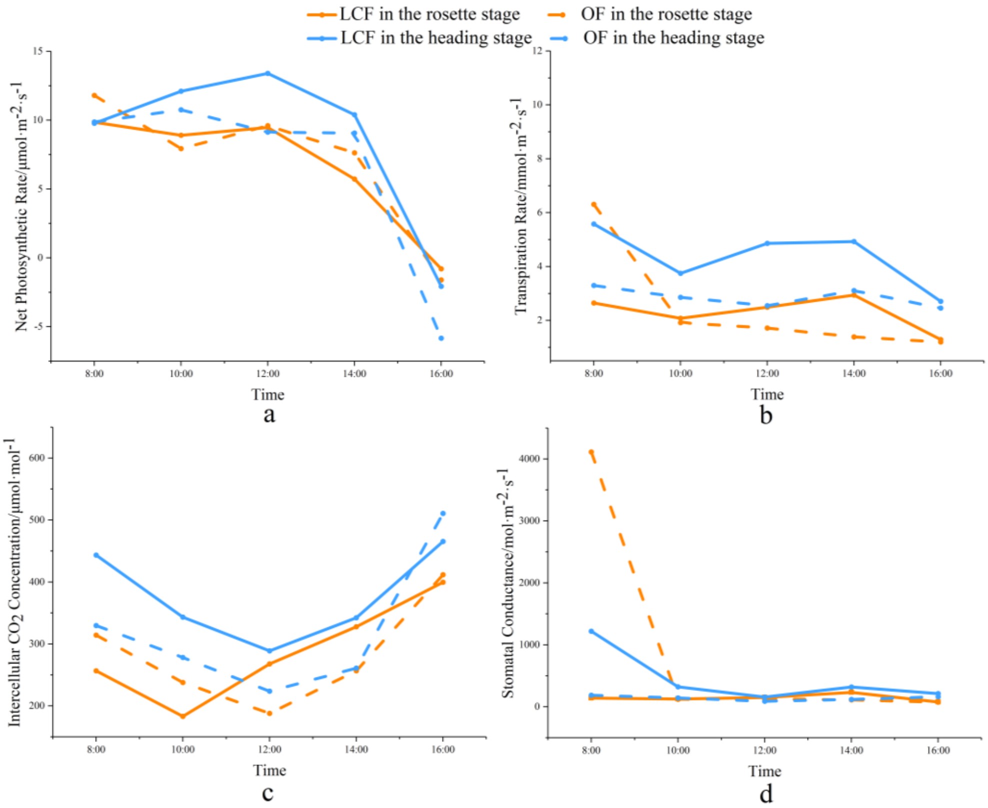


**Figure 11.** Effects of light conversion films (LCF) and ordinary film (OF) on (**a**) net photosynthesis, (**b**) transpiration rate, (**c**) intercellular $CO_2$ concentration, and (**d**) stomatal conductance.

3.5.2. Effect of LCF on Crop Yield and Quality

Crop yield and quality directly reflect the growth of crops. Table 7 shows the statistics of production yield and quality. Every 667 m2 of the first crop increased by 228.92 kg under LCF compared with OF: an 8.97% increase. For the second crop, the yield increased by 364.2 kg: a 39.53% increase. The yield of the first and second crops under LCF was significantly different from that under OF. The LCF treatment significantly increased the total soluble sugar content and reduction−type Vitamin C. The total soluble sugar content of the first and second crops were 0.66% and 0.2% higher under LCF than under OF, respectively, and there was a very significant difference ($p < 0.01$) between LCF and OF. Compared with OF, reduction-type Vitamin C increased by 21.09% and 1.41%, respectively, and there was a very significant difference in reduction-type Vitamin C content reduction in the first crop between the two treatments. The soluble protein of the first crop in the LCF greenhouse was 0.06% higher than that of the OF greenhouse, indicating a very significant difference. The soluble protein of the second crop in the LCF greenhouse decreased by 0.02% compared with the OF greenhouse, and there was a significant difference between them.

**Table 6.** Effects of light conversion film (LCF) and ordinary film (OF) on Photosynthetic Characteristics of plant leaves at different growth stages.

| Growth Period | Project | LCF | OF | Variable | *p* | Sig. |
|---|---|---|---|---|---|---|
| Rosette stage | Net photosynthesis /μmolm$^{-2}$s$^{-1}$ | 33.15 | 35.37 | −2.22 | 0.561 | NS |
| | Transpiration rate /mmolm$^{-2}$s$^{-1}$ | 11.45 | 12.54 | −1.09 | 0.696 | NS |
| | Intercellular $CO_2$ concentration /μmolm$^{-2}$ | 1436.33 | 1409.83 | +26.5 | 0.326 | NS |
| | Stomatal conductance/molm$^{-2}$s$^{-1}$ | 740.83 | 4558.67 | −3817.84 | 0.173 | NS |
| Heading stage | Net photosynthesis /μmolm$^{-2}$s$^{-1}$ | 43.6 | 32.98 | +10.62 | 0.370 | NS |
| | Transpiration rate /mmolm$^{-2}$s$^{-1}$ | 21.83 | 14.28 | +7.55 | 0.567 | NS |
| | Intercellular $CO_2$ concentration /μmolm$^{-2}$ | 1884.33 | 1604.83 | +279.5 | 0.005 | ** |
| | Stomatal conductance/molm$^{-2}$s$^{-1}$ | 2346.00 | 715.17 | +1630.83 | 0.048 | * |

Note: *p* indicates the significant difference between rosette stage and heading stage ($p < 0.05$), "*" indicates significant influence ($0.01 \leq p < 0.05$), "* *" indicates extremely significant influence ($0.001 \leq p < 0.01$) and "ns" indicates non-significant influence of factors.

**Table 7.** Effect of light conversion films (LCF) and ordinary film (OF) on crop yield and quality with different crops.

| Processing | Output (kg·(667 m$^2$)$^{-1}$) | | Total Soluble Sugar (%) | | Soluble Protein (%) | | Reduction-Type Vitamin C (mg·kg$^{-1}$) | |
|---|---|---|---|---|---|---|---|---|
| | First Crop | Second Crop | First Crop | Second Crop | First Crop | Second Crop | First Crop | Second Crop |
| LCF | 2782.28 | 1285.56 | 2.85 | 2.37 | 0.24 | 0.14 | 183.75 | 502.67 |
| OF | 2553.36 | 921.36 | 2.19 | 2.17 | 0.18 | 0.16 | 151.75 | 495.67 |
| Amplitude variation (%) | +8.97 | +39.53 | +30.14 | +9.22 | +33.33 | −12.50 | +21.09 | +1.41 |
| *p* | 0.030 | 0.001 | 0.001 | 0.003 | 0.005 | 0.047 | 0.001 | 0.367 |
| Sig. | * | ** | ** | ** | ** | * | ** | NS |

Note: *p* represents the significant difference between LCF and OF in the same column ($p < 0.05$), '*' represents a significant influence ($0.01 \leq p < 0.05$), '**' represents an extremely significant influence ($0.001 \leq p < 0.01$), and 'NS' represents a non-significant influence of factors.

## 4. Discussion

### *4.1. Effect of LCF on the Soil-Plant-Atmosphere Continuum of Greenhouse*

The greenhouse environment is an important condition affecting the growth and development of vegetables, especially out−of−season vegetable growth. Low temperature and weak light are two of the main factors limiting the growth and development of protected vegetables. Therefore, the transmittance, spectral transmittance, and irradiance of LCF and OF were tested in this study. According to the test results of light transmittance, the use of LCF can significantly improve the light transmittance in the greenhouse. The light transmittance of LCF greenhouse film is 8.67% higher than that of OF. Therefore, compared with OF, LCF improves the utilization efficiency of solar energy, and it can directly affect the growth and development of crops and fruit quality.

Red−orange light and blue−violet light, as the most effective light for photosynthesis of plants, directly affect the growth of crops. Through the detection of spectral transmittance of the two kinds of greenhouse films, it is found that under the same conditions, LCF greenhouse films can convert yellow−green light into red−orange light. Therefore, compared with OF, LCF improves the intensity of red−orange light band. The average values of LCF and OF in the red–orange light band are 88.1% and 86.8%, respectively. LCF is 1.3% higher than OF. The increase in red−orange light is conducive to the absorption of chlorophyll, thus promoting the growth of plants and fruits and effectively improving crop yield [22].

At the same time, the irradiance under the two kinds of greenhouse films was detected by spectrometers. It was found that LCF could improve the irradiation intensity in the greenhouse, thus effectively improving the photosynthetic capacity. In summary, it can be found that the use of LCF can improve the light intensity in the greenhouse, thereby improving the microclimate in the greenhouse and improving the crop growth environment.

Through the study of the air temperature in the greenhouse, it is found that the use of LCF can significantly improve average air temperature in the greenhouse, and the improvement effect can reach 2.07−6.75%. This is consistent with the results of Kou et al. [23] on the application of LCF in protected horticultural production. The use of LCF can increase air temperature by 0.7−1.8 °C. Moreover, it can increase the active accumulated temperature and effective accumulated temperature in the greenhouse compared with OF (Figure 12) by 2.06−2.79% and 6.54−9.34%, respectively. This is due to the Stokes displacement of LCF in the process of light conversion. The energy difference generated in the process of high−energy light excitation and low−energy light emission is released in the form of heat energy, which effectively improves the air temperature in the facility [23]. The path analysis of the monitored data showed that the increase in air temperature was strongly related to the yield of crops. For each 1 °C increase, the yield per mu (667 m2) increased by 1.008 kg.

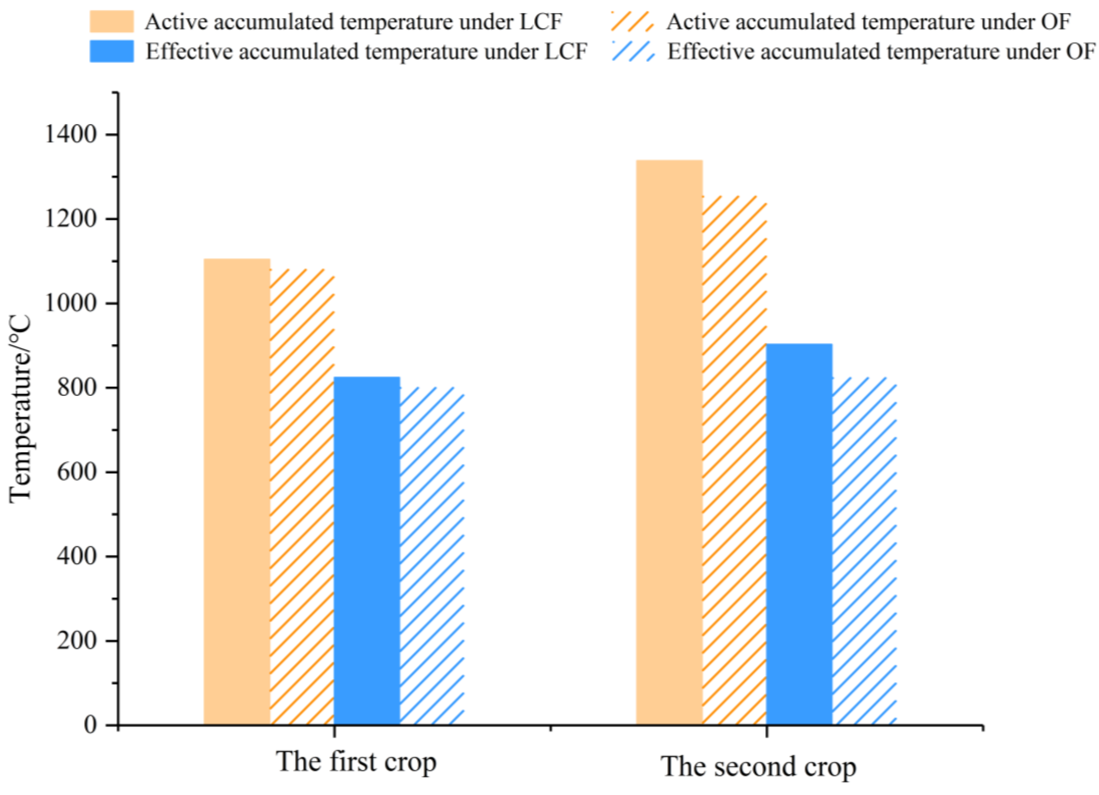


**Figure 12.** Effect of light conversion film (LCF) and ordinary film (OF) on accumulated temperature in greenhouse under different crops. (Note: Active accumulated temperature refers to the sum of daily active temperatures in a certain period of time or growing season of crops. Usually, the daily average temperature in the duration of more than or equal to 10 °C is accumulated to obtain the total temperature, which is called active accumulated temperature. The effective accumulated temperature is the sum of the effective temperature of crops in a certain growth period or all growth periods. In this paper, the sum of 5−25 °C in the whole growth period of crops is taken as the effective accumulated temperature).

The increase in air temperature is also clearly mapped to the self-parameters of crops. One day of the first crop heading stage (10:39−10:45 a.m. on 8 November 2019) was selected to measure the canopy temperature of the two crops covered with greenhouse film by using a thermal imager (keysight, Santa Rosa, CA, USA). Through three repeated measurements (Table 8), it was found that the average leaf canopy temperature under LCF was higher than 2.3 °C of OF greenhouse film, but there was no significant difference in the leaf canopy temperature under the two kinds of greenhouse film. This is because the stronger the light intensity, the higher the canopy temperature [24].

**Table 8.** Effects of light conversion film (LCF) and ordinary film (OF) on leaf canopy temperature at heading stage.

| Repeat | LCF | OF |
|---|---|---|
| Repeat 1 | 22.7 °C | 18.8 °C |
| Repeat 2 | 19.2 °C | 15.4 °C |
| Repeat 3 | 21.2 °C | 22.0 °C |
| *p* | 0.347 | |
| Sig. | NS | |

Note: *p* represents the significant difference between LCF and OF in the same column ($p < 0.05$), '*' represents a significant influence ($0.01 \leq p < 0.05$), '**' represents an extremely significant influence ($0.001 \leq p < 0.01$) and 'NS' represents a non-significant influence of factors.

Air humidity plays an important role in stomatal opening, photosynthesis, growth, development, and quality of crops. Too high or too low air humidity will damage the plant [25]. We found that air humidity in the LCF greenhouse was about 0.47−2.83% lower than that in the OF greenhouse. This was because LCF promotes the increase in air temperature in the greenhouse, thus reducing air humidity. Lettuce and cabbage, as leafy crops, require a low air humidity, if air humidity is too high, rhizome rot, diseases, and pest invasion can more easily occur. The air humidity in the LCF greenhouse was lower than that in the OF greenhouse, which could reduce the occurrence of diseases and pests.

Moreover, the increase in $CO_2$ concentration has both a direct and an indirect effect on plant growth and development, morphological structure, and internal physiological and biochemical functions. Studies have shown that if the $CO_2$ concentration in the atmosphere increases from 350 to 700 $mL \cdot L^{-1}$, the global crop yield and biomass would increase by 24−43% [26]. In the current study, the use of LCF was shown to increase the $CO_2$ concentration by 30.99−32.00%. This is because the use of LCF increases the transmittance of red and blue light, is conducive to the absorption of chloroplast pigment, and enhances the respiratory rate, thus increasing the $CO_2$ concentration [27].

The soil temperature is related to the growth and development of crops and affects the absorption of water and nutrients by plant roots. The current study revealed that, compared with OF, LCF significantly improves soil temperature in the greenhouse, with an increase range of 3.23−3.82%. This is because the use of LCF significantly increases the light transmittance and improves the air temperature in the greenhouse, effectively improving the soil temperature. The relationship between air temperature and soil temperature in the LCF and OF greenhouses is shown in Figure 13. In the LCF greenhouse, soil temperature increased by 14.47 °C for every 1 °C rise of air temperature. In the OF greenhouse, soil temperature increased by 14.23 °C for every 1 °C increase in air temperature. There was a clear soil temperature improvement (1.66% increase) in the LCF greenhouse relative to the OF greenhouse.

The findings of the current study reveal that LCF can effectively improve plant photosynthetic efficiency and light energy utilization. Compared with OF, LCF significantly improved the efficiency of photosynthesis at the heading stage, and crop Pn, E, Gs, and Ci were increased by 32.16%, 52.87%, 17.42%, and 228.42%, respectively. There was a very significant difference between LCF and OF between Ci and Gs. Moreover, LCF can convert part of ultraviolet light in sunlight and yellow and green light not needed by plants into the blue–violet light and red−orange light, which are beneficial to plant growth [21]. The increased amount of red light promotes plant photosynthesis. It was found that red light could increase chlorophyll content, and the greater the ratio of red light to blue light, the higher the chlorophyll content of leaves [13]. Red light can also enhance the stomatal opening of leaves, improve Gs, and increase the photosynthetic capacity of crops, which is conducive to their growth and development [28]. The increase in air temperature, $CO_2$ concentration, PAR, and soil temperature, as well as the promotion of photosynthesis, also ultimately determine the increase in yield. It was found that the crop yield using LCF increased by 8.97−39.53% compared with OF. This is consistent with the results of Liu Yang et al. [13], who found that strawberries treated with LCF matured 10 days in advance, the yield 27.86% higher than those treated with OF. The use of LCF can significantly improve the reduction-type Vitamin C content of strawberry fruit by 16.1−24.4% compared with OF [28]. The results of the current study support these findings. We found that LCF effectively increased the total soluble sugar (9.22−30.14%) and reduction-type Vitamin C (1.41−21.09%) contained in crops, and there was a very significant difference between LCF and OF.

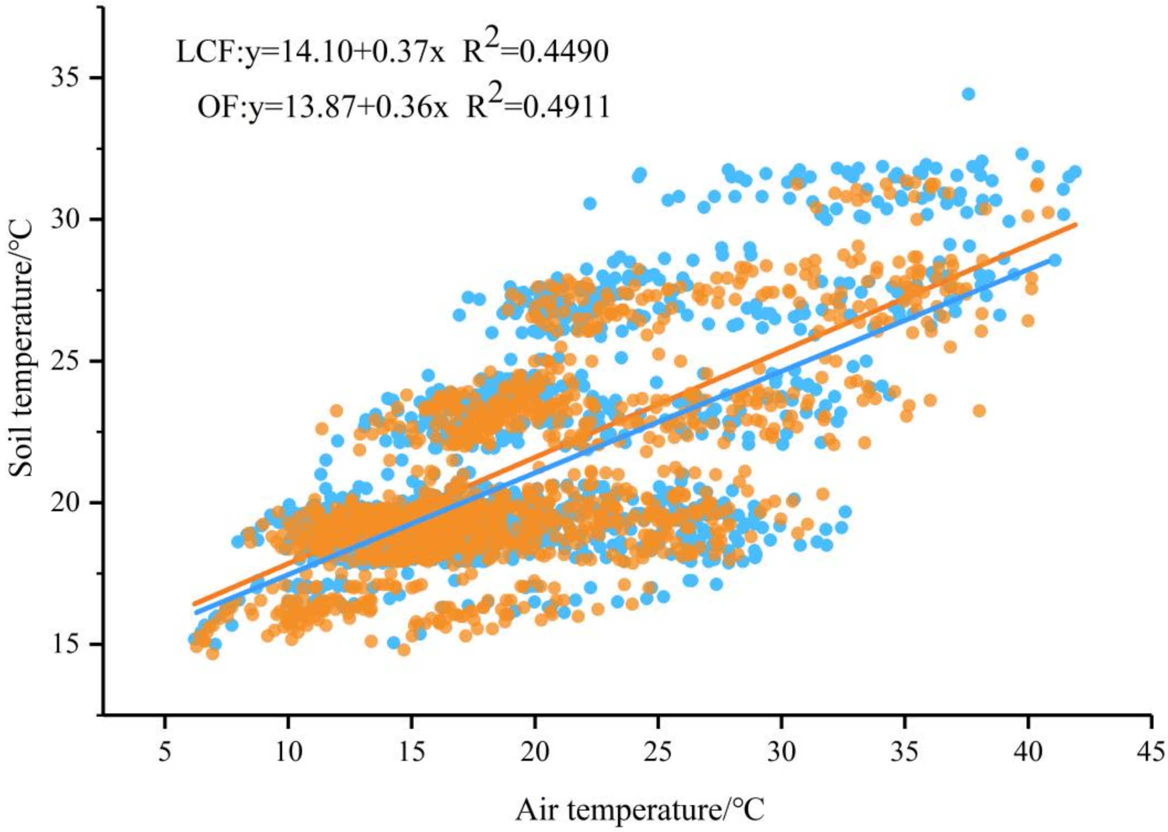


**Figure 13.** Correlation between air temperature and soil temperature under light conversion film (LCF) and ordinary film (OF). (The yellow dots indicate the correlation between light conversion film and air temperature and soil temperature, and the blue dots indicate the correlation of common membrane to air temperature and soil temperature.).

Table 9 lists the types of fill light lamps commonly used in domestic greenhouses and the characteristics of LCF, and it calculates the costs of different fill light treatments under ideal degrees.The required irradiation area is set as the area of the conventional greenhouse with an area of 260 $m^2$, and the service time is set as 3000 h. The HPS and led fill lamps of gavita and illumitex powerharvest brands, as well as the common LCF on the market, are selected as the calculation targets, respectively.

**Table 9.** Cost calculation of different types of fill lamps and light conversion films.

| | **HPS** | **LED** | **LCF** |
|---|---|---|---|
| Characteristic | Large energy consumption, large calorific value and many hidden dangers in operation. It is suitable for 10−year planning | Small size, high light efficiency, low power consumption, adapt to various harsh environments, and high one-time cost investment | Good tensile property, good light transmittance, dustproof, anti fog drop, anti-aging and light conversion function |
| Energy consumption (w) | 1055 | 580 | 0 |
| Illumination output (μmol/J) | 2100 | 1170 | – |
| Efficiency (mol/kWh) | 7.17 | 7.26 | – |
| Unit price of equipment ($) | $320 | $1200 | $0.1719−0.2813/m$^2$ |
| PPFD (μmol/m$^2$/s) | 250 | 250 | 250 |
| Area covered by each light source (m$^2$) | 8.4 | 4.68 | 260 |
| Total area (m$^2$) | 260 | 260 | 260 |
| Equipment demand | 31 | 56 | 260 m$^2$ |
| Total price of equipment ($) | $9920 | $67,200 | $44.694−73.138 |
| Power consumption ($/kwh) | $0.08 | $0.08 | 0 |
| Service duration (hour) | 3000 | 3000 | 3000 |
| Energy consumption cost ($/year) | $7849.2 | $7795.2 | 0 |
| Total cost ($) | $17,769.2 | $74,995.2 | $44.694−73.138 |

It can be seen from the table that the cost of lighting up the greenhouse with fill light lamps mainly includes fixed cost and variable cost (the total equipment price is fixed cost, and the energy consumption cost is variable cost). Although the energy consumption of an LED lamp is slightly lower than HPS, the initial construction cost is significantly higher than HPS. At the same time, in order to achieve the target PPFD (PPFD is set as the required value of leafy vegetables in this example), the energy consumption cost of LED lamps is comparable to that of HPS. The use of fill light also has the problems of large heating capacity. Therefore, it is also necessary to use high-power fans, air conditioners, and other cooling equipment, resulting in the increase in operation cost again.

As a basic equipment, the LCF replaces the OF, and does not need to pay other expenses during crop growth, and the production cost is significantly lower than that of the light supplement equipment. According to the experimental results, the use of LCF can significantly increase crop yield (8.97−39.53%), total soluble sugar (9.22−30.14%), and reduction−type Vitamin C (1.41−21.09%), significantly improving the indoor environmental conditions in cloudy weather and improve the photosynthetic utilization efficiency.

Although artificial lighting can improve the yield and quality of crops to a certain extent, it needs to consume significant costs and increase the production cost, which is difficult for most farmers to accept. LCF obviously improves the yield and quality of crops under the condition of low cost, and it has high utilization efficiency. As a new energy, rare earth is the main compound of LCF, which can be reused. It is a new way of green lighting.

### *4.2. Correlation between Microclimate Environment of Light Conversion Film Greenhouse*

Through correlation analysis of microclimate environment (air temperature, air humidity, $CO_2$ concentration, PAR, and soil temperature) in LCF greenhouse of two crops (Table 10), in the two crops, there were significant and extremely significant positive correlations between air temperature and soil temperature and between air humidity and $CO_2$

concentration, that is, with the increase in air temperature and air humidity, soil temperature and $CO_2$ concentration also increased. Among them, the correlation analysis results of the first crop show that the air temperature has a significant moderate positive correlation with PAR and soil temperature. It can be said that the rise of air temperature directly affects the PAR intensity and soil temperature in the greenhouse. At the same time, there is a significant positive strong correlation between air humidity and $CO_2$ concentration, as well as a very significant negative strong correlation between air humidity and PAR that is, with the increase in air humidity, PAR decreases. According to the above analysis, LCF can reduce the air humidity in the greenhouse, thus promoting the enhancement of PAR intensity. Other meteorological parameters have different degrees of positive and negative correlation. The correlation of air temperature to soil temperature and air humidity to $CO_2$ concentration in the second crop is the same as that in the first crop, but the intensity is significantly higher than that in the first crop, that is, there is a very significant positive correlation between air temperature to soil temperature and air humidity to $CO_2$ concentration. In addition, in the correlation analysis of the second crop meteorological data, there is a significant negative strong correlation between air temperature and air humidity, that is, with the increase in air temperature, the air humidity has a significant downward trend.

**Table 10.** Analysis of correlation coefficient of greenhouse environment under light conversion film.

| | | | **Air Temperature (°C)** | **Air Humidity (%)** | **$CO_2$ Concentration (mg·L$^{-1}$)** | **PAR (μmolm$^{-2}$S$^{-1}$)** | **Soil Temperature (°C)** |
|---|---|---|---|---|---|---|---|
| First crop | Air temperature (°C) | P | 1 | −0.32 | 0.293 | 0.474 * | 0.488 * |
| | | $R^2$ | 1 | 0.1024 | 0.086 | 0.225 | 0.201 |
| | Air humidity (%) | P | – | 1 | 0.546 * | −0.687 ** | −0.213 |
| | | $R^2$ | – | 1 | 0.298 | 0.472 | 0.045 |
| | $CO_2$ concentration (mg·L$^{-1}$) | P | – | – | 1 | −0.153 | 0.272 |
| | | $R^2$ | – | – | 1 | 0.023 | 0.074 |
| | PAR (μmolm$^{-2}$S$^{-1}$) | P | – | – | – | 1 | 0.258 |
| | | $R^2$ | – | – | – | 1 | 0.067 |
| | Soil temperature (°C) | P | – | – | – | – | 1 |
| | | $R^2$ | – | – | – | – | 1 |
| Second crop | Air temperature (°C) | P | 1 | −0.707 * | −0.291 | 0.409 | 0.768 ** |
| | | $R^2$ | 1 | 0.500 | 0.085 | 0.167 | 0.590 |
| | Air humidity (%) | P | – | 1 | 0.818 ** | −0.542 | −0.177 |
| | | $R^2$ | – | 1 | 0.669 | 0.294 | 0.031 |
| | $CO_2$ concentration (mg·L$^{-1}$) | P | – | – | 1 | −0.190 | 0.220 |
| | | $R^2$ | – | – | 1 | 0.036 | 0.048 |
| | PAR (μmolm$^{-2}$S$^{-1}$) | P | – | – | – | 1 | 0.258 |
| | | $R^2$ | – | – | – | 1 | 0.067 |
| | Soil temperature (°C) | P | – | – | – | – | 1 |
| | | $R^2$ | – | – | – | – | 1 |

Note: the correlation significance level of "**" is 0.01 (two tailed), and the correlation significance level of "*" is 0.05 (two tailed).

Combined with the correlation analysis of two crops, it can be found that the use of LCF greenhouse film can effectively enhance the PAR strength of greenhouse film, thus increasing the direct energy source of plant life activities, organic matter synthesis, and yield. In addition, the increase in air temperature promotes the increase in soil temperature and reduces the air humidity, thus reducing the disease and insect disasters caused by excessive air humidity, which is conducive to the growth and development of crops.

*4.3. Effect of LCF on the Greenhouse Environment under Different Weather Conditions*

Cloudy weather will lead to low temperature and weak light in the greenhouse, limiting the normal growth of crops. LCF can effectively convert the light source and supplement the light of the greenhouse, in the case of cloudy and insufficient sunshine, to help find a low−carbon production mode. Our analysis of the impact of LCF on the greenhouse environment under different weather conditions indicated that the use of LCF on sunny days significantly improved the greenhouse environmental parameters compared with OF, in which air temperature, $CO_2$ concentration, PAR and soil temperature increased by 0.20−2.08 °C, 37.75−396.31 mg·$L^{-1}$, 54.02−98.17 µmol $m^{-2}$ $S^{-1}$, and 0.03−2.34 °C, respectively. In addition, compared with OF, LCF also reduces the air humidity of the greenhouse, thus potentially reducing the occurrence of diseases and pests. The impact of LCF on greenhouse environment in cloudy and haze days was similar to that of the OF greenhouse, but air temperature, $CO_2$ concentration, PAR, and soil temperature were significantly higher than OF greenhouse, and air humidity was lower than OF greenhouse.

Therefore, the use of LCF is conducive to converting sunlight into light beneficial to the crops, ensuring that they receive sufficient light and improving air temperature and soil temperature in the greenhouse. Although the improvement effect of using LCF in cloudy weather is slightly lower than that in sunny weather, it is still higher than the air environment and soil environment observed in the OF greenhouse. This shows that, even in polluted weather, the use of LCF can effectively gather sunlight and convert it into favorable red−orange light and blue−purple light, improve the growth environment of plants, and thus, improve crop growth and yield. At the same time, the use of LCF also reduces the production cost relative to OF and provides a low−cost, energy−efficient, and sustainable approach to greenhouse lighting.

## 5. Conclusions

In this study, LCF is considered to be an effective method to increase the solar intensity in the facility. It was found that the transmittance, red−orange light band intensity, and irradiance of LCF were higher than that of OF. In the haze weather, the illumination in the greenhouse has been greatly improved, which improves the air temperature in the greenhouse, reduces the air humidity, and reduces the occurrence of diseases and pests. In addition, there was a positive correlation between soil temperature and air temperature under LCF, showing that soil temperature increased by 14.47 °C for every 1 °C increase in air temperature. Furthermore, compared with OF, LCF significantly ($p < 0.05$) increased the concentration of $CO_2$ and PAR, and accelerated the efficiency of crop photosynthesis, which enhanced the physiological growth of crops. We found that crop yield could be increased by 8.97−39.53%, and the total soluble sugar and reduction−type Vitamin C increased by 9.22−30.14% and 1.41−21.09%, respectively. Detailed results also indicated that photosynthesis at the heading stage was significantly stronger than that at the rosette stage, and it was generally higher under LCF than under OF (The net photosynthetic rate, transpiration rate, intercellular $CO_2$ concentration, and stomatal conductance under LCF were 10.62 µmol$m^{-2}s^{-1}$, 7.55 mmol$m^{-2}S^{-1}$, 279.5 µmol$m^{-2}$, and 1630.83 mol$m^{-2}S^{-1}$ higher than that of OF, respectively, and the intercellular $CO_2$ concentration and stomatal conductance were significantly different between LCF and OF). This study has realized the steady and low-carbon production of leaf vegetables. More greenhouse planting experiments are needed to further prove the crops such as eggplant, fruit, and root vegetables. Based on LCF, some supplementary measures, such as solar energy recycling, solar greenhouse film surface rainwater collection and utilization, and environmental optimization regulation based on Internet of Things, also require further exploration to optimize the greenhouse low carbon sustainable production system.

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