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Estimation of Thermal Performance and Heat Loss in Plastic Greenhouses with and without Thermal Curtains

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Abstract: Greenhouses are important for stable food production, but require large amounts of energy to maintain their microclimate in regions with harsh climates. This study assessed the internal thermal insulation performance of thermal curtains in double-layered plastic greenhouses in Korea in winter using cover surface temperature changes and heat transfer coefficients (U values). The thermal curtain performance increased as the temperatures of the inner cover surface increased and the outer cover surface decreased. The outer cover surface temperature with thermal curtains was almost uniformly 1.9 °C lower than that without thermal curtains, whereas the inner cover surface temperature was higher, demonstrating the warming effect of thermal curtain use. Under a constant indoor and outdoor air temperature difference, the daily average heating energy consumption was directly proportional to the U value. The U values were 2.76 W m^{-2} $°C^{-1}$ with thermal curtains and 3.85 W m^{-2} $°C^{-1}$ without thermal curtains. In double-layered plastic greenhouses that were covered with 0.1-mm-thick polyethylene, incorporating thermal curtains at night resulted in energy savings of about 28.7%, which was related to the decrease in U values. Installing and using thermal curtains at night in winter is a highly economical method for heating savings. These results can be used to promote energy savings in greenhouses in harsh climates.

Keywords: thermal insulation; cover surface temperature; energy consumption; U value

1. Introduction

Greenhouses have an important role in supporting stable vegetable production and supply in Korea [1]. However, one of the major limitations of greenhouses is their energy cost, because a suitable microclimate for vegetable production must be maintained regardless of severe external weather conditions, especially in winter [2–4]. In Korea, fossil fuels for heating greenhouses account for 30–40% of the total operation costs of protected horticultural structures, such as plastic greenhouses [5,6]. One method for reducing the heating costs of horticulture agriculture is in the development of renewable energy sources that can replace fossil fuels, and many recent studies have examined the application of renewable energy sources to greenhouses. Despite these efforts, it is currently difficult to satisfactorily supply greenhouses with renewable energy sources to replace conventional fossil fuels [7–10]. Instead, the use of thermal curtains, which is a passive method to decrease heat consumption in greenhouses, is currently the most economical, practical, and effective method for decreasing fossil fuel consumption [11–14]. Thermal curtains decrease the heating loads of greenhouses by increasing their thermal resistance, which decreases heat transfer between indoor and outdoor air. This heat transfer in greenhouses is expressed as the heat transfer coefficient (U value) for each section of material covering a greenhouse [4,14–18].

Arinze et al. [14] reported that double-layered greenhouses inflated with air with a fan had U values of 2.1 W m^{-2} $°C^{-1}$ in the closed shutter position and 4.4 W m^{-2} $°C^{-1}$ in the open shutter position, showing that the closed shutter position offered better insulation. Papadakis et al. [18] found that single- and double-polyethylene-covered greenhouses without thermal curtains had U values of 6.0–8.0 W m^{-2} $°C^{-1}$ and 4.2–6.0 W m^{-2} $°C^{-1}$, respectively, showing that a double-layered cover offered better insulation. Meanwhile, the Japan Greenhouse Horticulture Association [19] reported that double-layered greenhouses with and without thermal curtains had U values of 3.1–3.2 W m^{-2} $°C^{-1}$ and 3.8 W m^{-2} $°C^{-1}$, respectively. Moreover, Seginer et al. [20] and Nijskens et al. [21] reported the U values of double-layered greenhouses without thermal curtains to be 6.9–7.3 W m^{-2} $°C^{-1}$ and 4.8–6.4 W m^{-2} $°C^{-1}$, respectively. These results indicate that U values are not always suitable, and can be influenced by the type and condition of the material, convection, and radiation heat transfer process, greenhouse type, and the use of thermal curtains [18].

Therefore, although a number of researchers have experimentally studied the utility of thermal curtains in reducing heat loss in greenhouses, there is a need to analyze differences in the thermal insulating effect of greenhouses between those with and without thermal curtains according to various environmental conditions (e.g., indoor and outdoor air temperature difference, etc.) and greenhouse cladding material conditions [14]. Moreover, to the best of our knowledge, few studies have attempted to analyze the cover surface temperature and air temperature, the heat insulating effect (i.e., U values), and energy consumption with and without thermal curtains in single-span plastic greenhouses that are covered with double-layered polyethylene, which are used widely in Korea. Plastic greenhouse use has expanded rapidly worldwide, including in Europe, North Africa, South America, and China [22]. Of the 44,177 ha of single-span plastic greenhouse used to grow vegetables in Korea in 2014, 13,704 ha were double-layered greenhouses, and only 5669 ha had thermal curtains [1]; therefore, more research is required in order to support the expansion of thermal curtain use.

The objectives of this study were to quantify the effect of thermal performance on energy conservation in double-layered plastic greenhouses with and without thermal curtains. To this end, we measured the air and cover surface temperatures of greenhouses with and without thermal curtains, and analyzed the relationship between the insulating effects of experimental greenhouses and cover surface temperatures. In addition, we assessed the overall heat transfer coefficients (U values) and the energy consumption of greenhouses with and without thermal curtains.

2. Material and Methods

2.1. Experimental Greenhouse and System Description

Two single-span plastic greenhouse units were used in this study, one unit without thermal curtains (Figure 1a), and one that is equipped with thermal curtains (Figure 1b,c). The experimental greenhouses used in this research were double-layered, covered with a 0.1-mm-thick polyethylene film in both the inner and outer layers of the greenhouse. The inner useable floor area of the experimental greenhouse for cultivating plants was 225 m^2 (7.5 m × 30 m), the central height of inner cover was 3 m, and the distance between the inner and outer side layers was 25 cm. Strawberries were grown inside the experimental greenhouses. The two single-span plastic greenhouses were located in the Protected Horticulture Research Institute, South Korea (35°23′ N, 128°42′ E).

Figure 2 presents a schematic diagram of the experimental greenhouse with thermal curtains. Thermal curtains, which reduce the heat loss in plastic greenhouses during winter at night, were installed on the inner plastic cover between the inner and outer layers of the double-layered greenhouse. The upper and side walls of the greenhouses were covered with the thermal curtain, while the front and rear end walls were not covered, which is a common configuration in typical plastic greenhouses with thermal curtains in Korea. The thermal curtain, which was drawn over the inner cover surface of the double-layered greenhouse, had a thickness of 5 cm and was composed of polyethylene sheets and cotton. The thermal curtains were kept closed over the inner plastic cover at night (17:30–08:30)

(Figure 1b) and were opened by rolling up to the central beam of the inner cover during the day (08:30–17:30) (Figure 1c). The inner and outer layers of the side wall of the double-layered greenhouse were kept closed at night to maintain warmth, while the lateral walls automatically opened to allow for natural ventilation when the indoor air temperature during the day reached above 25 °C, representing the daily maximum temperature for fruit-bearing strawberry crops [23]. The lateral wall was opened and closed by rolling the inner and outer layers up or down using an electric motor.

The experimental greenhouses were equipped with two hot-water boilers, which distributed hot water through pipes that were installed over the length of the greenhouses at both sides of the inner layer to heat the indoor air of the greenhouses. Hot-water heating involves the circulation of boiler-heated warm water through pipes installed within the greenhouses, and uses the heat that was emitted from the surface during circulation. This type of heating requires time for water to heat; however, it also retains heat even after the boiler has been turned off. The hot-water boilers, a common heating system used in greenhouses in Korea, were operated at night. The heating temperature of the experimental greenhouse was set at 8 °C, which is the target temperature typically used by strawberry growers during the fruit-bearing period in Korea [23].

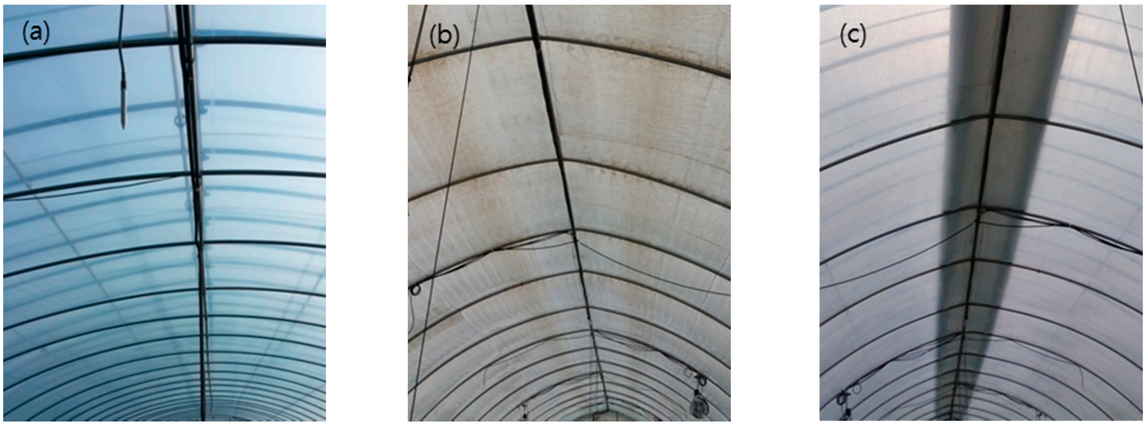

Figure 1. Images of the inside of the greenhouses: (**a**) without thermal curtains, (**b**) with thermal curtains closed over the inner plastic cover, and (**c**) with thermal curtains rolled up to the central beam of the inner cover.

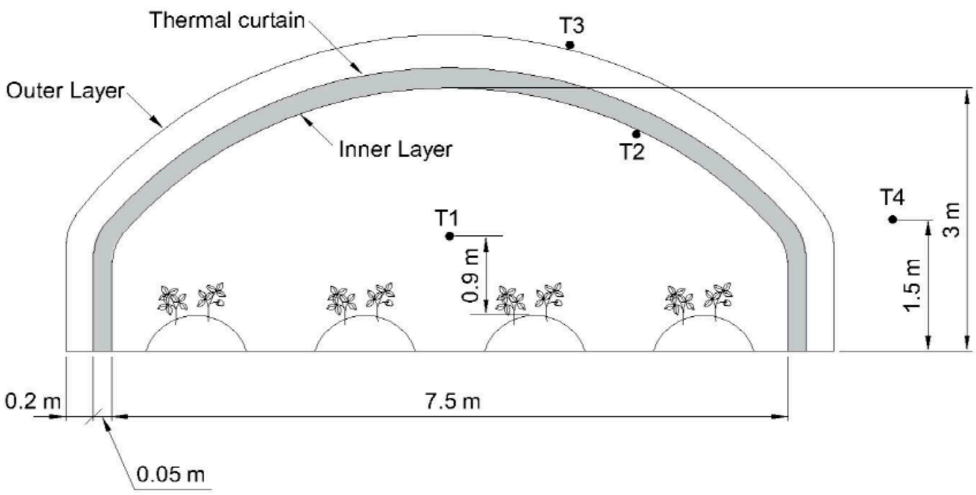

Figure 2. Schematic diagram of the experimental greenhouse with a thermal curtain: (T1) indoor air temperatures, (T2) inner cover surface temperatures, (T3) outer cover surface temperatures, and (T4) outdoor air temperatures.

2.2. Measurements

The measurements were carried out from 17:30 on 14 January 2016 to 08:30 on 28 January 2016 in winter. To comparatively analyze the heat efficiency and heat loss in plastic greenhouses with and without thermal curtains, this study continuously measured the inside and outside temperatures of the greenhouses, surface temperature and fuel use. The outdoor air temperatures were measured with two TempRetriever RH data loggers (MadgeTech, Warner, NH, USA), which were located 1.5 m above the ground. The indoor air temperature was measured with three TempRetriever RH data loggers located 0.9 m above the furrows. The accuracy of the TempRetriever RH data loggers is ±0.5 °C within a range of −40–80 °C, with a measurement resolution of 0.1 °C. The inner and outer cover surface temperatures were measured with two TR-0206 screw-down sensors (T&D Corporation, Matsumoto, Japan), and stored in a data logger (model TR-71wf; T&D Corporation, Matsumoto, Japan) with an accuracy of ±0.3 °C over a range of −20–80 °C and resolution of 0.1 °C. The air and cover surface temperatures of the greenhouses were automatically recorded at 10-min intervals, and the averages of each sensor were used. The fuel consumption at night was recorded daily with a flowmeter.

2.3. Energy Analysis Methodology

The energy saving effect with and without thermal curtains of the double-layered greenhouse can be estimated based on the thermal curtain effectiveness (CEF) [15]:

$$\mathrm{CEF} = \left(\mathrm{Q}_{WITHOUT} - \mathrm{Q}_{WITH}\right) / \mathrm{Q}_{WITHOUT} \tag{1}$$

where $\mathrm{Q}_{WITHOUT}$ is the average energy consumption at night without thermal curtains (kWh) and Q_{WITH} is that with thermal curtains.

The rate of energy consumption, assuming steady state conditions, was determined using the following equation [4,15–18]:

$$\mathrm{Q} = \mathrm{U}\, A_C \Delta\mathrm{T} \tag{2}$$

where Q is the average nighttime energy consumption, U is the overall heat transfer coefficient (U value), A_C is the greenhouse cover area, and ΔT is the average indoor and outdoor air temperature difference at night.

3. Results and Discussion

3.1. Greenhouse Temperature

The environmental conditions were measured over 14 consecutive days. The outdoor air temperature varied between −13.1 and 12.2 °C (average: −1.6 °C). The outdoor air temperature at night, from 17:30 to 08:30, varied between −13.1 and 4.4 °C (average: −4.1 °C).

Figure 3a,b show the daily variation in air temperature inside and outside the greenhouse and the inner and outer cover surface temperatures without and with thermal curtains for 14 consecutive days. The inner surface temperature was similar to the indoor air temperature, and the outer surface temperature was similar to the outside air temperature. The indoor air and surface temperatures during the day, which was not heated, followed the same trend as the outdoor air temperature.

During this 14-day period, the indoor air, inner surface, and outer surface temperatures of the greenhouse without thermal curtains varied between 3.8 and 26.8 °C, 0.1 and 25.9 °C, and −10.6 and 19.6 °C, respectively, while the greenhouse with thermal curtains showed variations between 6.0 and 28.4 °C, 3.8 and 32.5 °C, and −11.9 and 19.5 °C, respectively, when the outdoor air temperature ranged from −13.1 and 12.2 °C. The average indoor air, inner surface, and outer surface temperatures during the day were 18.8, 15.7, and 7.7 °C without thermal curtains and 19.1, 18.9, and 6.5 °C with thermal curtains, respectively, whereas the average indoor air, inner surface, and outer surface temperatures at night were 8.8, 5.7, and −2.3 °C without thermal curtains and 8.6, 8.3, and −4.2 °C with thermal curtains, respectively. The greenhouses with and without thermal curtains both had temperatures that were similar to the target heating temperature (8 °C). However, the lowest temperature of the greenhouse without thermal curtains was 4.2 °C lower than the target heating temperature, and 2 °C lower for the greenhouse with thermal curtains. This appears to be due to the limitations in the heating capacity of hot-water boilers and the increase in the hat-water boiler heating times on days with extremely low external temperatures (e.g., −13.1 °C). Overall, these results confirmed that greenhouses with thermal curtains offered superior management of the greenhouse environment than greenhouses without thermal curtains.

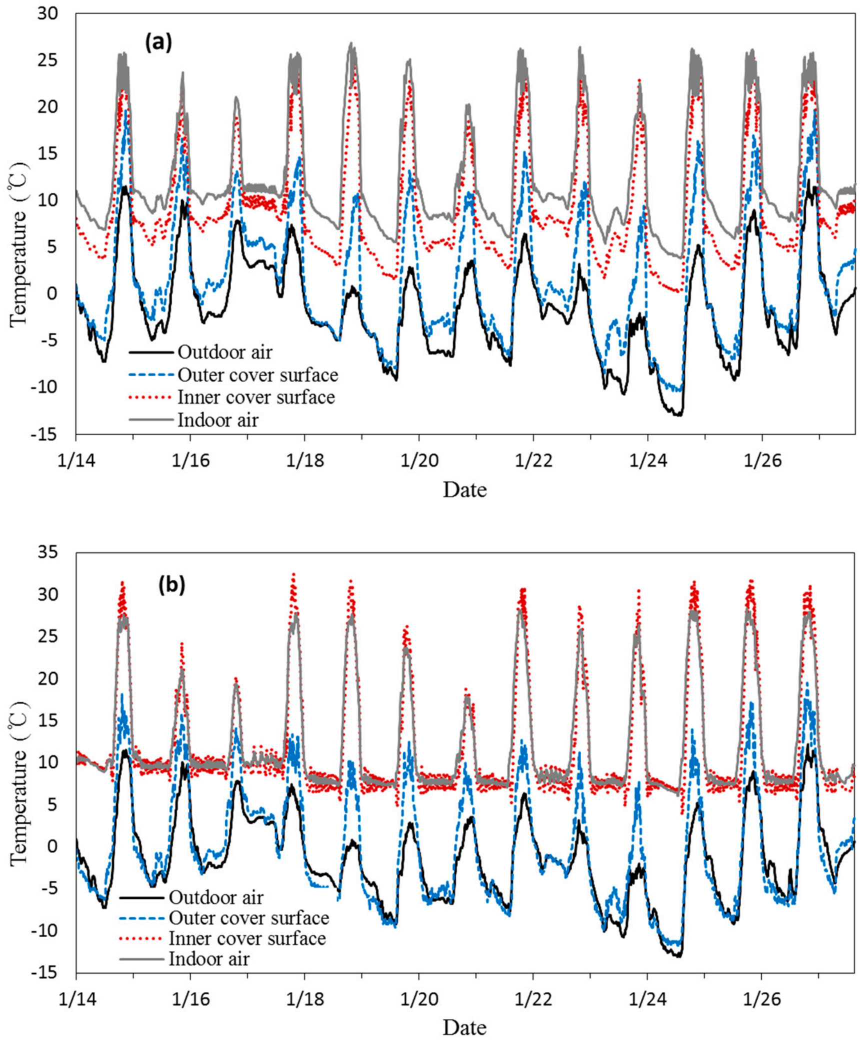

Figure 3. Variations in outdoor air, outer cover surface, inner cover surface, and indoor air temperature from 14–28 January 2016, (**a**) without thermal curtains, and (**b**) with thermal curtains.

Figure 4a shows the temperature variations of the experimental greenhouse without thermal curtains on a typical sunny winter day. The indoor air, inner cover surface, and outer cover surface temperatures reached maximums of 25.1, 22.8, and 13.1 °C at about 13:30, respectively, when the highest outdoor air temperature of 2.9 °C occurred at 13:30, and minimums of 5.5, 1.6, and −8.0 °C at 07:30, respectively, close to when the lowest outdoor air temperature of −9.3 °C appeared at 07:50. The results in this study followed the same trends as reported previously [7,24] that maximum indoor and cover surface temperatures occurred at about 14:00 and the minimum indoor temperature occurred before sunrise. The temperature difference (indoor air—inner cover surface) between indoor air and inner cover surface during the day ranged from 2.0 to 7.1 °C, while that at night ranged from 3.0 to 4.3 °C. The average temperature differences between indoor air and the inner cover surface during the day and at night were 4.1 and 4.0 °C, respectively. The temperature differences were lower and more uniform at night than during the day, because artificial heating was used at night and the effect of solar radiation was excluded. Seginer et al. [20] reported mean temperature differences between indoor air and the inner cover surface in double-layered greenhouses at night of 4.4 °C, when the external temperature was 10.5 °C. Nijskens et al. [21] reported a difference between the inside air temperature and the inner surface temperature of 12.4 °C in a double-layered greenhouse on a day with a cloudless sky and an external temperature of −10 °C. There were substantial differences between the results reported by Nijskens et al. [21] and the results of this study, which appears to have been caused by differences in experimental conditions, as Nijskens et al. [21] set the internal temperature at 20 °C, and the external temperature at −10 °C. The outer cover surface temperature at night was similar or slightly lower than the outdoor air temperature. The temperature difference (outer cover surface—outdoor air) ranged from −0.3 to 2.3 °C (average: 0.6 °C). Seginer et al. [20] reported that the difference between the outer cover surface of a double-layered greenhouse and outdoor air temperature was 0.5 °C at nighttime with an outside temperature of 10.5 °C. Meanwhile, Nijskens et al. [21] reported that this difference was 2.3 °C when the outdoor temperature was −10 °C on a day with clear sky.

Figure 4b presents the temperature variations in the experimental greenhouse with the thermal curtain on a typical sunny winter day. When the highest outdoor air temperature of 2.9 °C occurred at 13:30, the maximum indoor air, inner cover surface, and outer cover surface temperatures were 23.7 °C at 12:20, 26.3 °C at 12:20, and 12.5 °C at 13:10, respectively. Meanwhile, the minimum indoor air and outer cover surface temperatures were 7.0 °C at 07:20 and −9.6 °C at 07:20, near the occurrence of the minimum outdoor air temperature of −9.3 °C at 07:50. These results also followed similar trends as previous studies [7,24]. The minimum inner cover surface temperature was 4.8 °C at 08:30, the moment when the thermal curtain was rolled up. The temperature difference (indoor air—inner cover surface) between the indoor air and the inner cover surface during the day ranged from −3.5 to 4.4 °C, while that at night ranged from −1.2 to 4.4 °C. The average temperature differences between indoor air and inner cover surface during the day and at night were 0 and 0.2 °C, respectively. At night, the temperature difference between the upper and lower points of the inner cover surface showed decreasing cyclic changes, with peak-to-peak differences between approximately 2.5 and 0.3 °C. This was because the thermal curtain stored heat from the high indoor air temperature of the greenhouse at night, likely due to the fact that the thermal curtain was in contact with the inner layer, but separated from the outer layer by about 20 cm. Figure 4b also shows that the inner cover temperatures from 07:40 to 11:00 were lower than those of indoor air temperatures, while those from 11:10 to 16:10 were higher. This was due to the fact that the thermal curtain, when rolled up during the day, acted as a thermal mass due to the absorption of solar radiation during the day. From 17:30 to 08:30, the outer cover surface temperature was around 1.1 °C lower than outdoor air temperature due to radiant cooling [22,25,26]. When comparing the greenhouses with and without thermal curtains, this result means that, on clear nights, the effect of radiant cooling of the outer cover surface would be much higher if a plastic greenhouse were equipped with thermal curtains than without thermal curtains. In addition, the thermal insulation effect of the greenhouse increased with increasing temperature difference between the inner and outer cover surface of the double-layered greenhouse.

Figure 5 shows the variations in inner cover surface temperature between the greenhouses equipped with and without thermal curtains at night as a function of the indoor air temperature. The inner cover surface temperature was linearly dependent on indoor air temperature [22]. The slope of the regression model equation without thermal curtains (y = 1.21x − 4.92 (R^2 = 0.92)) was steeper than that with thermal curtains (y = 0.80x + 1.36 (R^2 = 0.49)), which is indicative of an increase of 1.21 °C in the inner cover surface temperature for every 1 °C of indoor air temperature without thermal curtains, but an increase of 0.8 °C in inner cover surface temperature for every 1 °C of indoor air temperature with thermal curtains. Moreover, the R^2 value for the relationship with thermal curtains was lower, and the dispersion of scatter plot was higher, when compared to that without thermal curtains (Figure 5). The decreased R^2 values and increased dispersion of the scatter plot indicate a lower correlation between inner cover surface temperature and indoor air temperature. These results are in agreement with those of Figure 4b.

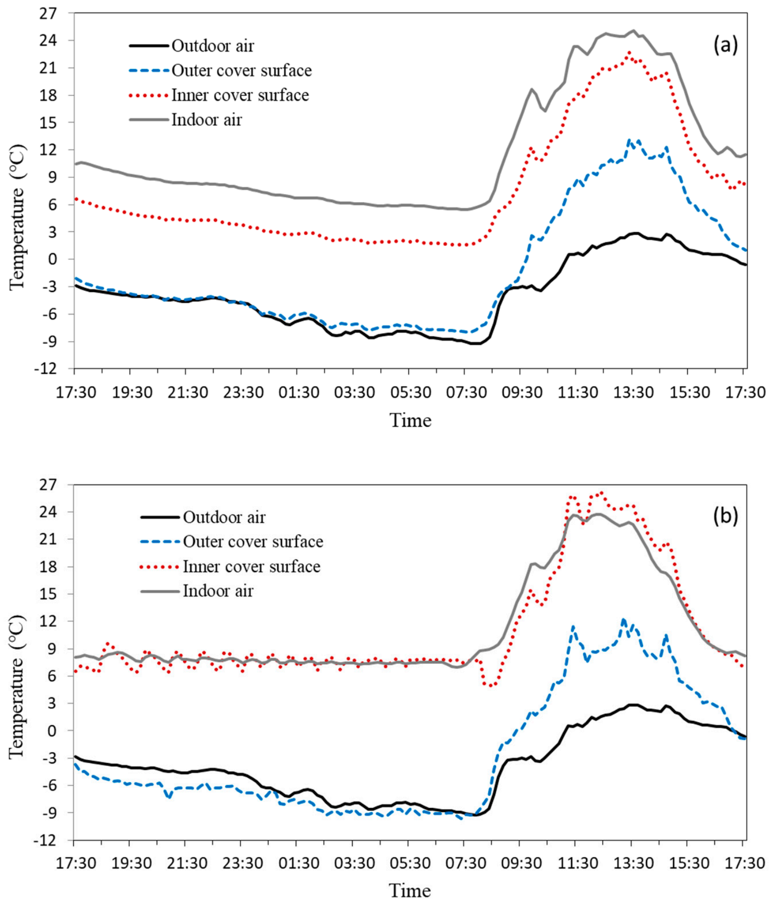

Figure 4. Variations in outdoor air, outer cover surface, inner cover surface, and indoor air temperature on a sunny day (19–20 January 2016) (**a**) without thermal curtains and (**b**) with thermal curtains.

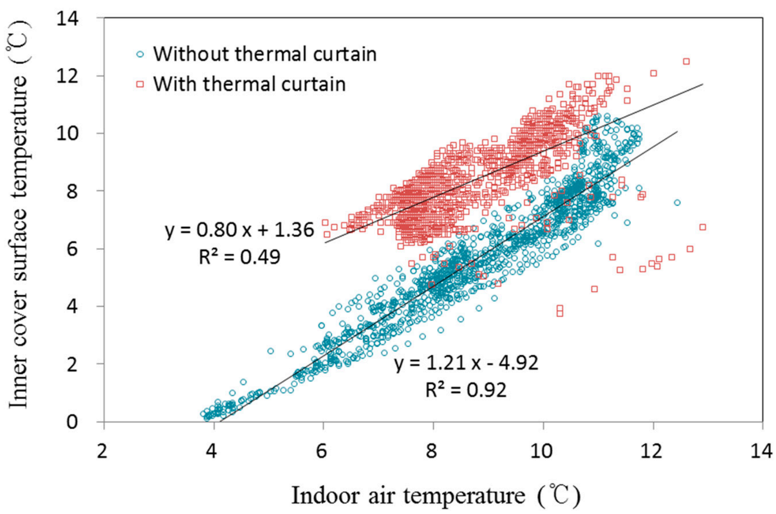

Figure 5. Inner cover surface temperature as a function of indoor air temperature without and with thermal curtains.

Figure 6 shows the temperature comparisons of the outer cover surface as a function of the outdoor air temperature with and without thermal curtains at night. The relationship between the outer cover surface temperature and outdoor air temperature without and with thermal curtains were $y = 0.90x + 1.31$ ($R^2 = 0.86$) and $y = 0.89x - 0.63$ ($R^2 = 0.84$), respectively. In this case, the outer cover surface temperature showed a fairly high level of dependence with outdoor air temperature. The slopes of the regression equation without and with thermal curtains were similar (0.90 and 0.89, respectively). In contrast, the equation for the greenhouse with thermal curtains showed a y-intercept of the curve that was 1.94 °C lower than that without thermal curtains.

These results clearly demonstrate that the heat insulation effect of the greenhouse increased based on the higher temperature of the inner cover surface and lower temperature of the outer cover surface [22]. Moreover, the use of the thermal curtain system increased the heat insulation effect, which yielded an inner cover surface temperature that was closer to the indoor air temperature and an outer cover surface temperature that was closer to the outdoor air temperature [27]. These results imply that increasing the heat insulation effect using thermal curtains would be highly effective for promoting energy savings.

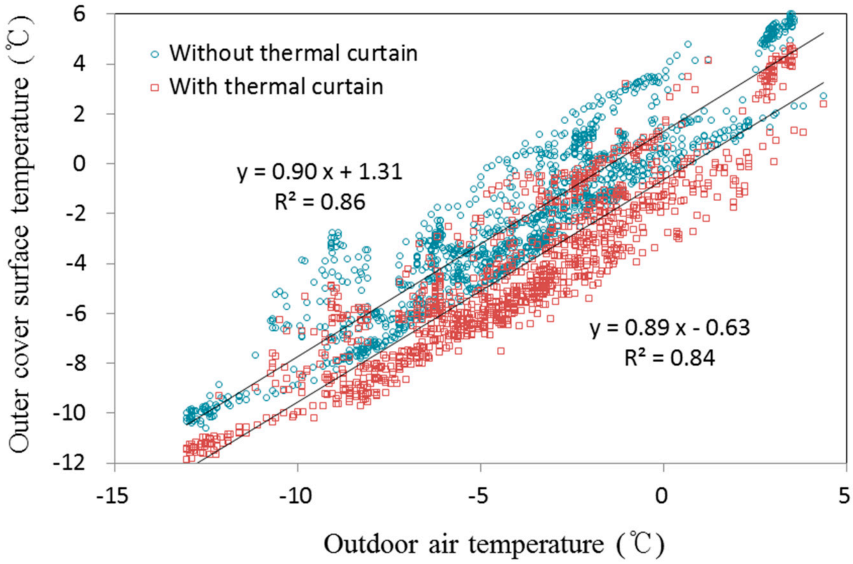

Figure 6. Outer cover surface temperature as a function of outdoor air temperature without and with thermal curtains.

3.2. Assessment of Energy Consumption and U Values

Figure 7 shows the daily experimental greenhouse energy consumption as a function of the indoor and outdoor air temperature difference with and without thermal curtains. Each point in Figure 7 represents the average energy consumption for one night. With increasing indoor and outdoor air temperature difference, energy consumption tended to increase. The average fuel consumption for one night was calculated as 191 kWh at an average air temperature difference of 12.6°C with thermal curtains and 267.8 kWh at an average air temperature difference of 12.8 °C without thermal curtains.

The value of CEF determined from Equation (1) was 0.287, indicating an energy saving effect of 28.7% by incorporating the thermal curtain on the inner plastic cover between the inner and outer layers of the double-layered greenhouse.

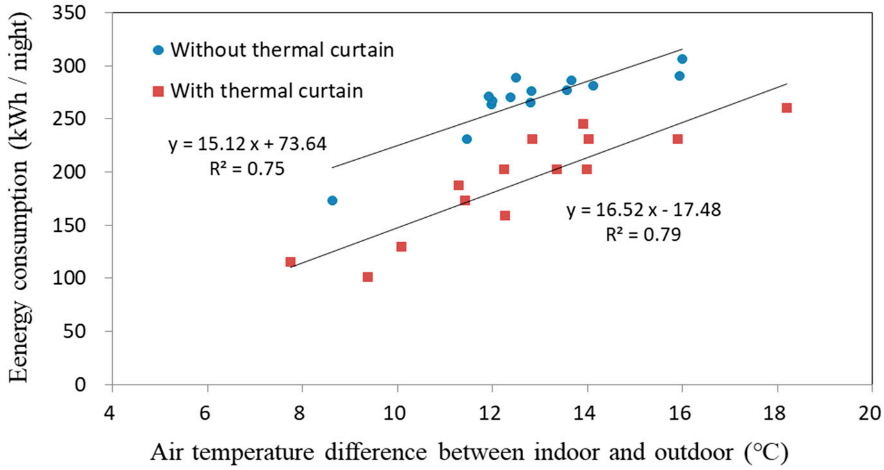

Figure 7. Energy consumption as a function of the indoor and outdoor air temperature difference without and with thermal curtains.

It should be noted that energy consumption depended on the indoor and outdoor air temperature differences and U values, as derived from Equation (2). However, in this experiment, the energy saving effect with thermal curtains was mainly represented by a decrease in U values because the indoor and outdoor air temperature differences were approximately the same, with (12.6 °C) and without (12.8 °C) thermal curtains (Table 1). The average U values with and without thermal curtains were 2.76 and 3.85 W m^{-2} $°C^{-1}$ in Equation (2), respectively. Regarding the direct effects of the U values, the energy consumption of a plastic greenhouse decreased by 70.8 kWh when the U values decreased by 1 W m^{-2} $°C^{-1}$. This indicated that the energy consumption for heating greenhouses depends on the U value, and installing thermal curtains for use at night is an economical and useful method to promote heating savings. In addition, the results of this study can be used to promote the use of thermal curtains in horticultural agriculture in Korea, as well as in other countries, to decrease operation costs.

Table 1. Comparison of U values and energy consumption of the greenhouses with and without thermal curtains.

Condition	U Value (W m^{-2} $°C^{-1}$)	Energy Consumption (kWh)	ΔT (°C)
With thermal curtain	2.76	191.0	12.6
Without thermal curtain	3.85	267.8	12.8

4. Conclusions

The thermal insulation effect of a plastic greenhouse was evaluated based on air and cover surface temperature changes and U values. When the greenhouses with and without thermal curtains had similar indoor and outdoor air temperatures, the greenhouse with thermal curtains exhibited a greater inner and outer cover surface difference than that without thermal curtains. Regarding the outer cover surface temperatures, the temperature of the greenhouse with thermal curtains was almost uniformly 1.9 °C lower than that without thermal curtains at night during the experimental period. The greenhouses with and without thermal curtains reached maximum air and cover surface temperatures that were between 12:20 and 13:30, and minimum air and cover surface temperatures at 7:20–7:50, demonstrating a particular need for heating during this period. The minimum inner cover surface temperature of the greenhouse with thermal curtains occurred at 08:30, the moment when the thermal curtains were rolled up.

The U values had an important role in determining the heating energy consumption in the greenhouse, and the U value and fuel usage rates were closely correlated, which was 2.76 W m^{-2} $°C^{-1}$ with thermal curtains and 3.85 W m^{-2} $°C^{-1}$ without thermal curtains. Regarding energy consumption and U values in the greenhouses with and without thermal curtains, the energy consumption decreased by 70.8 kWh with a 1-W m^{-2} $°C^{-1}$ decrease in U value. Installing thermal curtains is an effective method to promote heating savings, and the use of thermal curtains in greenhouses at night could yield energy savings of 28.7%, which is similar to the difference in the U values between greenhouses with and without thermal curtains. Therefore, thermal curtains are an effective method for decreasing U values by increasing thermal insulation. The results of this study are particularly applicable to greenhouses commonly used in Korea; however, they can be applied to similar set-ups in similarly harsh climates.

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Author Contributions: Hyung-Kweon Kim designed the study and wrote the paper; Geum-Choon Kang provided important comments on the results and conclusions; Jong-Pil Moon and Tae-Seok Lee collected and analyzed the data; Sung-Sik Oh checked the analysis results; All of the authors also reviewed the paper.

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

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