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Determination of the Effect of a Thermal Curtain Used in a Greenhouse on the Indoor Climate and Energy Savings

Sedat Boyacı [1], Atilgan Atilgan [2], Joanna Kocięcka [3,*], Daniel Liberacki [3], Roman Rolbiecki [4] and Barbara Jagosz [5]

[1] Department of Biosystem Engineering, Faculty of Agriculture, Kırşehir Ahi Evran University, 40100 Kırşehir, Turkey
[2] Department of Biosystems Engineering, Faculty of Engineering, Alanya Alaaddin Keykubat University, 07425 Alanya, Turkey; atilgan.atilgan@alanya.edu.tr
[3] Department of Land Improvement, Environmental Development and Spatial Management, Poznań University of Life Sciences, 60-649 Poznań, Poland
[4] Department of Agrometeorology, Plant Irrigation and Horticulture, Faculty of Agriculture and Biotechnology, Bydgoszcz University of Science and Technology, 85-029 Bydgoszcz, Poland
[5] Department of Plant Biology and Biotechnology, University of Agriculture in Kraków, 31-120 Krakow, Poland
* Correspondence: joanna.kociecka@up.poznan.pl

Abstract: In order to reduce the impact of outdoor extreme weather events on crop production in winter, energy saving in greenhouses that are regularly heated is of great importance in reducing production costs and carbon footprints. For this purpose, the variations in indoor temperature, relative humidity and dew point temperature in the vertical direction (2 m, 4 m, 5.7 m) of thermal curtains in greenhouses were determined. In addition, depending on the fuel used, the curtains' effects on heat energy consumption, heat transfer coefficient, carbon dioxide equivalents released to the atmosphere and fuel cost were investigated. To reach this goal, two greenhouses with the same structural features were designed with and without thermal curtains. As a result of the study, the indoor temperature and relative humidity values in the greenhouse with a thermal curtain increased by 1.3 °C and 10% compared to the greenhouse without a thermal curtain. Thermal curtains in the greenhouse significantly reduced fuel use (59.14–74.11 $m^3 \cdot night^{-1}$). Considering the heat energy consumption, the average heat energy consumption was 453.7 $kWh \cdot night^{-1}$ in the greenhouse with a curtain, while it was 568.6 $kWh \cdot night^{-1}$ in the greenhouse without a curtain. The average heat transfer coefficient (U) values were calculated at 2.87 $W \cdot m^{-2}$ °C with a thermal curtain and 3.63 $W \cdot m^{-2}$ °C without a thermal curtain greenhouse. In the greenhouse, closing the thermal curtain at night resulted in heat energy savings of about 21%, related to the decrease in U values. The use of a thermal curtain in the greenhouse reduced the amount of CO_2 released to the atmosphere (116.6–146.1 $kg \cdot night^{-1}$) and fuel cost (USD 21.3–26.7$\cdot night^{-1}$). To conclude, extreme weather events in the outdoor environment adversely affect the plants grown in greenhouses where cultivation is performed out of season. A thermal curtain, used to reduce these adverse effects and the amount of energy consumed, is essential in improving indoor climate conditions, providing more economical greenhouse management and reducing the CO_2 released into the atmosphere due to fuel use.

Keywords: greenhouse microclimate; energy productivity; overall heat transfer coefficient; energy consumption

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Citation: Boyacı, S.; Atilgan, A.; Kocięcka, J.; Liberacki, D.; Rolbiecki, R.; Jagosz, B. Determination of the Effect of a Thermal Curtain Used in a Greenhouse on the Indoor Climate and Energy Savings. *Energies* **2023**, *16*, 7744. https://doi.org/10.3390/en16237744

Academic Editor: David Borge-Diez

Received: 9 November 2023
Revised: 22 November 2023
Accepted: 22 November 2023
Published: 24 November 2023

1. Introduction

Continuous global population growth has significantly increased food demand [1]. In order to fulfil these needs, measures are increasingly being used to help plants grow as well as to adapt to ongoing climate change [2–6]. Another solution is conducting agriculture in a controlled environment, such as a greenhouse, which provides alternative, suitable conditions for growing crops all year. Greenhouse farming is one of the most common approaches to creating favourable microclimates for plant growth. This cost-effective cultivation strategy meets global food security and environmental sustainability criteria [7]. However, greenhouse cultivation is the most energy-intensive sector in the agricultural industry [8]. Heating is a critical part of greenhouse farming, as it is necessary to achieve the optimum temperature for plant growth during winter. When designing a greenhouse, selecting suitable materials can positively affect energy requirements and fuel consumption [9,10]. The greenhouse atmosphere, or air quality, can impact plant growth and crop quality. The degree of control that can be exercised over the greenhouse atmosphere will at least partially depend upon the type of greenhouse structure being used and the technology available [11]. For this reason, it is crucial to take necessary heat-saving measures by constructing greenhouse structures according to the region's climatic conditions and reducing production costs due to heating costs [12]. However, the correct design of the heating system selected for greenhouses is important regarding energy savings and reductions in initial investment costs [13]. Energy saving is the most important challenge in greenhouse cultivation, as heating costs can rise to more than 40% of the total production cost [14]. Heating costs in high-tech greenhouses that are regularly heated take first place or second place after labour, depending on the region's climate, among operating expenses. Heating costs in regularly heated greenhouses in the Mediterranean region take second place after labour costs at 20–25%, while they take first place in cold regions [15]. One method of reducing heating costs in horticultural agriculture is the development of renewable energy sources that can replace fossil fuels. In recent years, many studies have investigated rainwater use and the application of renewable energy sources to greenhouses [16]. Despite these efforts, it is currently difficult to provide sufficient energy for greenhouses with renewable energy sources that will replace traditional fossil fuels. Instead, using thermal curtains, a passive method to reduce heat consumption in greenhouses, is currently the most economical, practical and effective method to reduce fossil fuel consumption [17,18]. For heat conservation in greenhouses, some technical measures, such as reducing the losses in the transmission of heat energy to the greenhouse, using thermal curtains and wind protection, have been applied [19]. Although the rates of heat energy that can be saved with these technical measures vary between 5 and 40%, the most heat savings can be achieved with thermal curtains [20]. The necessary light (PAR) for photosynthesis reaches the greenhouse by collecting these curtains during daylight hours. Since all of the heat energy required for heating in temperate climatic regions and 70–75% in cold regions is needed at night, significant heat savings can be achieved when the system is designed with thermal curtains and the material is selected well [21,22].

The heat-saving rates of the curtains used in greenhouses vary depending on the impermeability of the curtains [23,24]. Teitel et al. [25] reported that around 40% of energy savings can be achieved by using aluminised curtains due to the lower heating demand at night. On the other hand, [26] examined the effect of an aluminised thermal curtain on the energy balance and microclimate in greenhouses and reported that the energy savings with an aluminised curtain is 15%. Thermal curtains provide additional thermal resistance by reducing heat transfer in the environment [27,28]. Thermal curtains reduce heating loads by increasing the thermal resistance of greenhouses, which reduces 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 the greenhouse [25,29]. Kim et al. [18] reported that the energy-saving effect of greenhouses is mainly represented by a reduction in the overall heat transfer coefficient (U value). The energy consumed by a plastic greenhouse decreased by 70.8 kWh when the U value decreased by 1 $W \cdot m^{-2}$ °C. Greenhouse cultivation constitutes an essential part of agricultural production in Turkey. The greenhouses cover an area of approximately 81,088.2 hectares. Glass and plastic-covered greenhouses constitute the majority of this area (53,091.2 ha). Increasing energy costs in production in such a large area cause producers to discuss the profitability of heating. The use of thermal curtains, which have been increasingly used in greenhouses for energy conservation in recent years, has great importance for energy savings. For this reason, there is a need for further studies on the indoor climate of heat curtains installed in high-tech greenhouses in Turkey in recent years, the fuel savings they will provide, fuel costs and the CO_2 released into the atmosphere by fossil fuels.

This study aimed to determine the differences in indoor climate parameters by giving the same amount of energy to greenhouses with and without thermal curtains. Moreover, the purpose was to identify the effect of thermal curtains on energy savings. This study conducted statistical tests to consider the hypothesis that average temperatures, relative humidity and average dew point temperature in greenhouses with and without thermal curtains are significantly different. In addition, the average heat energy consumption, fuel consumption and costs, heat transfer coefficient and CO_2 equivalent released into the atmosphere were also compared.

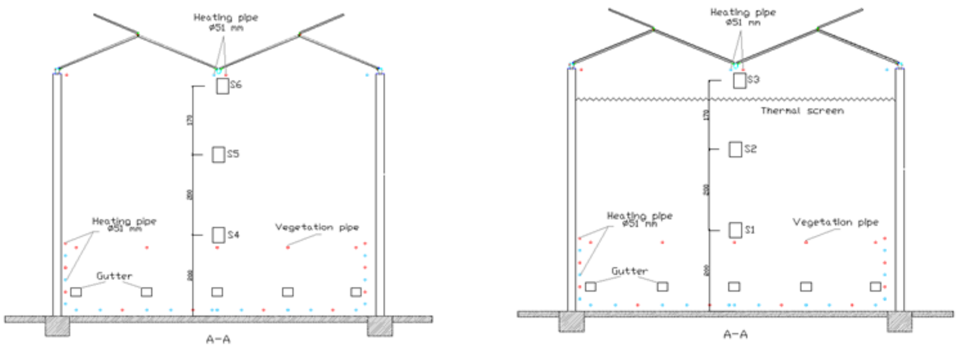
2. Materials and Methods

The experiment was carried out in February 2022 in two separate greenhouses located at Kırşehir Ahi Evran University, Kırşehir, Türkiye (39°08′02″ N 34°07′08″ E, 1082 m above sea level). The greenhouses, oriented north–south, were covered with glass walls (4 mm thick). Ventilation in greenhouses was enabled by ventilation flaps on the roof. The ventilation opening rate was 4% of the greenhouse floor area. Netting was used to prevent insects from entering the greenhouse through the ventilation openings. Dimensions and technical specifications of the greenhouses used in the research are given in Table 1.

Table 1. Technical characteristics of the experimental greenhouses.

Greenhouses	Technical Specifications
Type	Venlo
Cover material	4 mm glass
Side wall height	6 m
Ridge height	6.50 m
Width	8 m
Length	27 m
Ground area	216 m^2
Heating system	On the floor, side wall and roof

Two greenhouses were used in this study, one without a thermal curtain (Figure 1a) and one equipped with a thermal curtain (Figure 1b).



(**a**) (**b**)

Figure 1. Locations of sensors placed in the greenhouse (**a**) without thermal curtain and (**b**) with thermal curtain (red dots indicate warm water and blue dots cold water).

A thermal curtain (PS 55) consisting of transparent acrylic and aluminium strips with a shading rate of 55% and an energy-saving rate of 58% was used for heat protection in the greenhouses. The curtain was rolled up during the day in the curtained greenhouse to allow solar radiation to penetrate the greenhouse. In order to determine the effects of the thermal curtain in the greenhouses, the day was divided into two periods: the hours when the curtains were open and closed. In the first period, thermal curtains were opened by rolling up during the day at 08:00–17:00 (day: D), and in the second one, the thermal curtain was kept closed at night at 17:00–08:00 (night: N).

In this study, indoor temperature, relative humidity, dew point temperature, heat transfer coefficient, heat energy consumption and consumed fuel were regularly measured in greenhouses with and without thermal curtains to compare the two greenhouses. The outdoor air temperatures, relative humidity and wind speed were measured at the meteorology station located 4 m above the ground. The indoor air temperature was measured with Onset HOBO U12 data loggers, which recorded temperature and relative humidity values. These devices can measure temperature in the range of −20–70 °C with an accuracy of ±0.35 °C, and relative humidity measurements between 5% and 95% with an accuracy of 2.5%. Measurements in greenhouses were recorded at 30 min intervals. The fuel consumption was recorded daily with a flow meter.

In the greenhouse with a thermal curtain, the sensors under the curtain were placed at 2 m (S_1) and 4 m (S_2) from the ground. The third sensor was placed above the thermal curtain at a height of 5.70 m (S_3) from the ground, between the curtain and the ridge. In the greenhouse without a thermal curtain (control greenhouse), sensors were placed at the same locations (2 m: S_4, S_5: 4 m and S_6: 5.7 m), as in the thermal-curtained one.

In both greenhouses, tomatoes were grown. Natural gas was used as a fuel for heating, and heating pipes were placed on both side walls along the greenhouse and the length of the floor. Moreover, pipes were placed on the tomato plant row for vegetation heating. In order to determine the differences in the greenhouses with and without a thermal curtain, firstly, the indoor climate parameters were measured by giving the same amount of energy to the greenhouses. Then, both greenhouses were kept at the same internal temperature (15 °C), and the amount of fuel consumed, heat transfer coefficient, CO_2 equivalent emitted to the atmosphere and fuel costs were determined.

Heat energy transferred to the greenhouse based on natural gas consumption was calculated with Equation (1) [30].

$$Q = B_y \cdot H_u \cdot \eta_t \tag{1}$$

In this equation, Q = heat energy consumption (kWh), B_y = fuel consumption (m^3), H_u = lower calorific value of the fuel used ($kWh \cdot m^{-3}$), η_t = total efficiency of the heating system (%).

The overall heat transfer coefficients in the greenhouses were calculated with Equation (2) [19].

$$U = \frac{Q}{A_c \cdot (T_i - T_o)} \tag{2}$$

In this equation, U = overall heat transfer coefficient ($W \cdot m^{-2}$ °C), A_c = greenhouse surface area (m^2), T_i: greenhouse air temperature under the curtain (°C), T_o: outside temperature (°C).

The thermal curtain efficiency (TCE), evaluated according to [31], was calculated by Equation (3).

$$TCE = [(Q_{lus} - Q_{ls})/Q_{lus}] \tag{3}$$

In this equation, TCE = heat energy saving of thermal curtain (%), Q_{lus} = heat energy consumption in a greenhouse without a thermal curtain (kWh), Q_{ls} = heat energy consumption in a greenhouse with a thermal curtain (kWh).

The CO_2 emission of the fuel used in greenhouse heating to the atmosphere was calculated with Equation (4) [22].

$$SEGM_y = B_y \cdot H_u \cdot FSEG \tag{4}$$

In this equation, $SEGM_y$ = CO_2 emission amount (kg equivalent CO_2), FSEG = CO_2 emission conversion coefficient according to fuel type (kg equivalent $CO_2 \cdot kWh^{-1}$).

One sample *t*-test was used to determine the differences between greenhouses with and without thermal curtains using the GLM procedure of Windows Version of SPSS (SPSS 15.0 Windows Evaluation Version Release 15.0).

3. Results and Discussion

3.1. Determination of the Climate Parameters Outside of the Greenhouse

During the experiment, the outdoor temperature of the greenhouse was determined as 1.47 °C on average (−6.70–9.90 °C). During the hours when the thermal curtain was open, the outdoor temperature averaged 3.9 °C (−1.9–9.9 °C). Furthermore, during the hours when the thermal curtain was closed, an average of 0.1 °C (−6.7–8.4 °C) was measured. During the experiment, the minimum and maximum of the relative humidity values were measured between 35% and 97%, with an average of 73%, outside the greenhouse. An average of 63% was measured, between the minimum and maximum of 35 and 90%, of the relative humidity values outdoors when the curtains were open. In the hours when the curtain was closed, it was measured at between 47 and 97%, with an average of 78% (Figure 2).

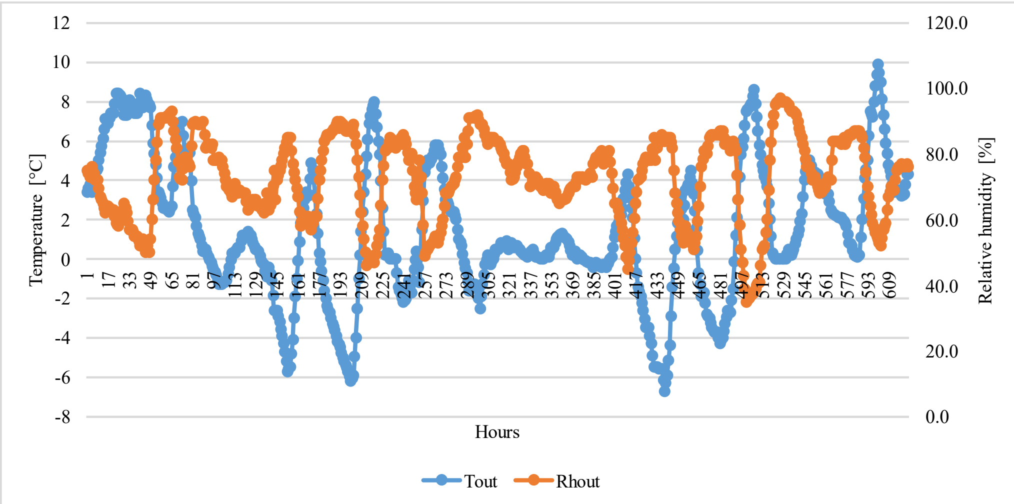


Figure 2. Variations in outdoor temperature (Tout) and relative humidity values (Rhout).

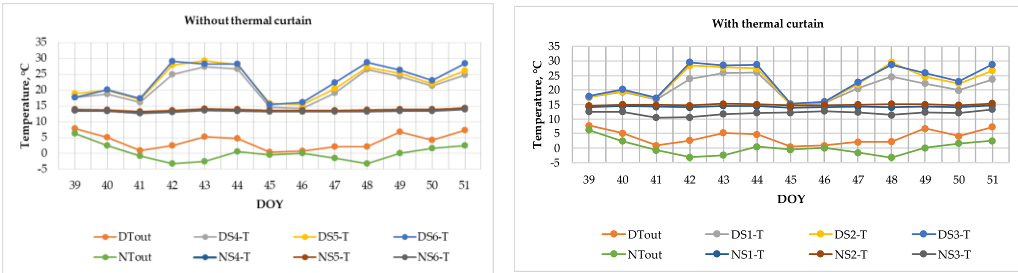
Greenhouse indoor air temperature depends mainly on outdoor climatic conditions (ambient temperature and solar radiation) and greenhouse design parameters [32]. Greenhouse management in arid and semi-arid areas is quite complex. Generally, the growing season includes the coldest and most rainy months of the year, and high relative humidity and low temperatures at night make it difficult to reach optimum growing conditions [33]. It can be seen from Figure 2 that extreme weather events in the greenhouse outdoor environment will adversely affect crop production. As the researchers reported in the conducted study, since the low temperature and high relative humidity values measured outdoors negatively affected the indoor greenhouse climate, it is essential to regulate the indoor climate for economic production.

The minimum and maximum values of outdoor solar radiation were measured at between 0 and 759.9 W·m^{-2}, with an average of 106.32 W·m^{-2}. Outdoor average solar radiation values were 273.2 W·m^{-2} (3.1–759.9 W·m^{-2}) during the hours when the curtain was open. Moreover, it was between 0 and 319.2 W·m^{-2} and 11.1 W·m^{-2} during closed hours. Especially during winter, every joule of sunlight is free energy input into the greenhouse, reducing heating costs [34]. For this purpose, the curtains were closed during the hours when the radiation values in the greenhouse started to decrease, and the energy was kept indoors. The wind speed values measured outdoors were 2.2 m·s^{-1} on average (0–13.9 m·s^{-1}). During the hours when the curtain was open, the outdoor wind speed values were measured at 2.3 m·s^{-1} between a minimum and maximum of 0 and 7.2 m·s^{-1};

they were measured at 2.1 m·s^{-1} between 0 and 13.9 m·s^{-1} when closed. Heat losses due to wind speed are at their lowest level in greenhouses with good curtain tightness [35]. For this reason, wind speed should be considered in determining the overall heat transfer coefficient of greenhouse gases.

3.2. Determination of the Climate Parameters of Indoor Greenhouse

The study revealed the differences between indoor temperature, relative humidity and dew point temperatures when the same amount of energy is applied in greenhouses with and without a thermal curtain. Accordingly, the variation in the temperature values measured during the hours when the curtains are open and closed in the greenhouse is given in Figure 3a,b.



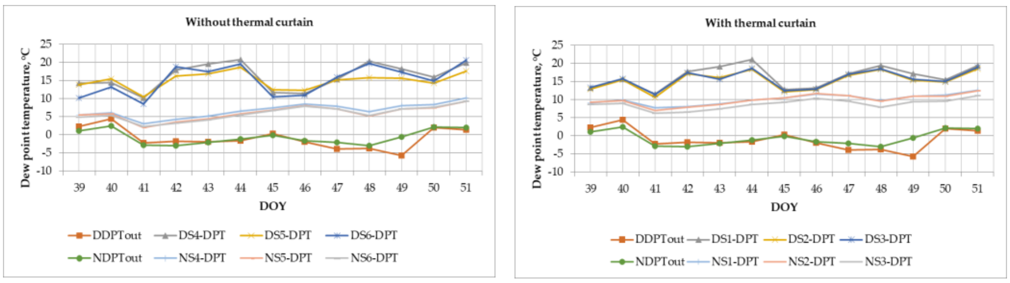
(**a**) (**b**)

Figure 3. Average temperature values measured indoors in the greenhouse (**a**) without thermal curtain and (**b**) with thermal curtain.

During the daytime hours when the thermal curtain was open (08:00–17:00), in the greenhouse with a thermal curtain, the temperatures every 30 min intervals were read from the sensors, and then the average temperatures were calculated as 20.8 °C at 2 m (DS_1-T), 22.6 °C at 4 m (DS_2-T) and 23.3 °C at 5.7 m (DS_3-T). In the control greenhouse, the average temperatures were estimated at 21.3 °C at 2 m (DS_4-T), 22.6 °C at 4 m (DS_5-T) and 23.2 °C at 5.7 m (DS_6-T) (Figure 3a,b). It was determined that the temperatures rise towards the roof area from the greenhouse floor during these hours when the thermal curtain is open. Thus, it was determined that the temperatures increased vertically from the greenhouse floor to the roof area.

During the nighttime hours when the thermal curtain was closed (17:00–08:00), in the greenhouse with a thermal curtain, the average temperature measured in the vertical direction was 14.3 °C at 2 m (NS_1-T), 15.0 °C at 4 m (NS_2-T) and 12.1 °C at 5.7 m (NS_3-T). During these hours when the thermal curtain is closed, temperatures tend to rise towards the roof area from the greenhouse floor. However, it was determined that these temperatures remained below the curtain due to the thermal curtain. In the greenhouse without a thermal curtain, the temperatures were 13.7 °C at 2 m (NS_4-T), 13.7 °C at 4 m (NS_5-T) and 13.3 °C at 5.7 m (NS_6-T) (Figure 3a,b). It was determined that the increased temperatures at the fourth meter of the greenhouse without a thermal curtain showed that the temperatures increased towards the roof area in the vertical direction due to the absence of a curtain (Figure 3a,b). This situation caused an average of 1.3°C difference between the temperatures under the curtain level (at 4 m) in the greenhouses with and without a thermal curtain. As a result of the statistical analyses, it was determined that the difference between the average temperatures in the greenhouses with and without thermal curtains was found to be statistically significant ($p < 0.01$). The authors of [36] reported that the temperature at 1.56 m during the daytime was higher than at the heights of 0.23 and 0.93 m, but the highest temperature was at 0.23 m at night and the lowest was at 1.56 m. The greenhouse's temperature and relative humidity distributions varied according to the intensity of solar radiation, depending on the height above the ground surface. It was reported that the greatest temperature and humidity gradients occurred at the peak of solar radiation at noon [37]. The curtain helps to keep thermal energy close to the plants and prevents heat losses from radiating into the cold night sky air to ensure good heat dissipation in the greenhouse [38]. The study conducted by [18] found that the temperature in greenhouse without thermal curtain was 2 °C lower than the temperature in the greenhouse with a thermal curtain. Moreover, the lowest temperature of the greenhouse without thermal curtains was 4.2 °C lower than the target heating temperature. Results confirmed that greenhouses with thermal curtains created a better indoor greenhouse environment than greenhouses without thermal curtains. The authors of [39] showed that polyester thermal curtains can keep the air temperature in the tunnel at 4.8 °C higher than outside. The maximum heating effect of the PE curtain was found to be only 2.5 °C during the test period. The optimum temperatures for growing tomato plants are 17–27 °C. When temperatures drop below 13 °C and rise above 30 °C, it reduces plant growth, pollen formation, pollen viability and germination ability [40]. Similar to these studies, the temperature values increased from the greenhouse floor to the roof area during the daytime when the curtain was open. At night, while the temperature values were kept under the curtain in the greenhouse where the curtain was used, the temperature increased towards the roof area where the curtain was not used. This situation made it difficult for the internal temperatures to reach 15 °C in the greenhouse where the thermal curtain was not used. As can be seen from the figures, the temperature remained at the plant level using the thermal curtain. While the indoor temperature was kept at 15 °C in the greenhouse with a curtain, it was measured at 13.7 °C on average in the greenhouse without a curtain. In addition, the internal temperature values in the greenhouse without a thermal curtain reached critical levels that would negatively affect tomato cultivation. The study determined that heating was necessary to keep the indoor environment of the greenhouse at suitable values for plant cultivation and that heat conservation measures should be taken to reduce the heat energy requirement. Increasing heat conservation measures are also necessary for more economical production by reducing the share of heating required for tomato production in energy costs.

In this study, the variation in the average relative humidity values measured in the vertical direction (2 m, 4 m and 5.7 m) in greenhouses with and without a curtain during day and night hours is given in Figure 4a,b.



(**a**) (**b**)

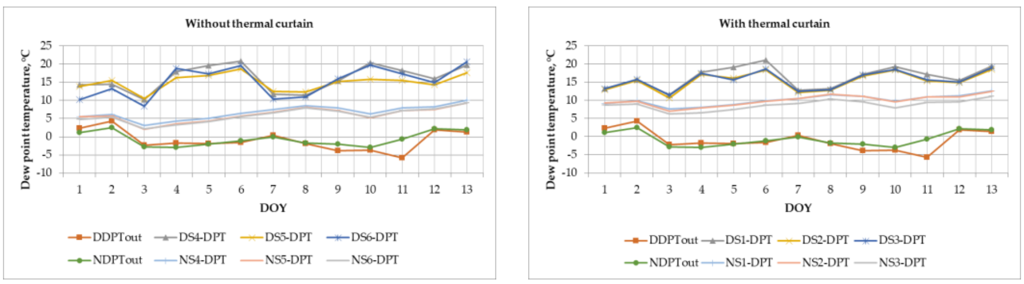
Figure 4. Average relative humidity values measured indoors in the greenhouse (**a**) without thermal curtain and (**b**) with thermal curtain.

During the daytime hours when the thermal curtain was open (08:00–17:00), in the greenhouse with a thermal curtain, the average relative humidity measured in the vertical direction reached 70% at 2 m (DS_1-T), 61% at 4 m (DS_2-T) and 60% at 5.7 m (DS_3-T). In the greenhouse without a thermal curtain, the values were measured at 60% at 2 m (DS_4-T), 51% at 4 m (DS_5-T) and 59% at 5.7 m (DS_6-T) (Figure 4a,b). The increase in temperatures from the greenhouse floor to the roof area during the opening hours of the thermal curtain caused the relative humidity to decrease in the vertical direction.

During the nighttime hours when the thermal curtain was closed (17:00–08:00), in the greenhouse with a thermal curtain, the average relative humidity measured in the vertical direction was 69% at 2 m (NS_1-T), 66% at 4 m (NS_2-T) and 71% at 5.7 m (NS_3-T). In the greenhouse without a thermal curtain, the values were 59% at 2 m (NS_4-T), 56% at

4 m (NS_5-T) and 57% at 5.7 m (NS_6-T) (Figure 4a,b). In the curtained greenhouse, the low temperatures in the roof area caused the relative humidity values to increase in this region because the temperature was below the curtain. On the other hand, in the greenhouse without a thermal curtain, the relative humidity values were measured as lower because the temperatures tended to increase towards the roof area. When the relative humidity values measured at the level under the curtain (4 m) at night in both greenhouses were compared, it was determined that the relative humidity values under the thermal curtain were 10% higher in the greenhouse with the thermal curtain. As a result of the statistical analyses, it was found that the difference between the average relative humidity in the greenhouses with and without thermal curtains was statistically significant ($p < 0.01$). In the study of [41], the improvements in the insulation of heated greenhouses led to changes in the microclimate of the protected crops. In addition, it was determined that atmospheric humidity was much higher in insulated greenhouses than in conventional greenhouses due to the restricted air exchange. Also, [42] reported that the relative humidity in the greenhouse where tomato plants were grown increased to 10–15% due to the aluminised polyester curtain. The relative humidity for the tomato plant should be around 50–60%; under 50% relative humidity, the stigma dries up and over 80% of the pollen is damaged [43]. It is recommended that the optimal relative humidity range be between 50 and 70% during all growth stages of tomatoes. Studies also showed that tomato pollination increased significantly when the relative humidity was around 60% [44]. In this research, as stated by previous studies, it was determined that the thermal curtain increased the indoor relative humidity values. However, this increase did not pose a problem for plant growth. An important reason for this was the correct design of the heating system in the greenhouse. Heating systems placed on the greenhouse's side wall, floor and roof helped to control the indoor relative humidity. The authors of [39] measured the average nightly relative humidity in tunnels with polyester and PE thermal curtains and tunnels without thermal curtains as 79.8%, 93.7% and 91.7%, respectively. However, the average nighttime relative humidity of the outside air was 89% during the experimental period. It was found that the average nighttime relative humidity indoors, in the PE curtain tunnel, was 5.2% higher than outside when the PE curtain was pulled at night. The researchers stated that the relative humidity increased due to the decrease in the air exchange rate of the PE curtain, and this caused an increase in the indoor dew point temperature. In the study, the average relative humidity value of the indoor environment was lower in the greenhouse without curtains, while it was 3% higher in the greenhouse with thermal curtains. For this reason, controlling the indoor dew point temperatures in the greenhouse during cultivation is very important.

In this study, the variation in the average dew point temperature values measured in the vertical direction (2 m, 4 m and 5.7 m) in greenhouses with and without a thermal curtain during day and night hours is given in Figure 5a,b.



(**a**) (**b**)

Figure 5. The dew point temperature values measured in the greenhouse (**a**) with a thermal curtain and (**b**) without a thermal curtain.

During the daytime hours when the thermal curtain was open (08:00–17:00), in the greenhouse with a thermal curtain, the average dew point temperature measured in the vertical direction was 16.3 °C at 2 m (DS_1-T), 15.3 °C at 4 m (DS_2-T) and 15.6 °C at 5.7 m (DS_3-

T). In the greenhouse without a thermal curtain, the values were 16.1 °C at 2 m (DS_4-T), 15.0 °C at 4 m (DS_5-T) and 15.2°C at 5.7 m (DS_6-T). It was determined that the indoor temperature values in both greenhouses were above the dew point temperatures during the daytime hours. Therefore, no condensation occurred indoors during daylight hours (Figure 5a,b).

During the nighttime hours when the thermal curtain was closed (17:00–08:00), in the greenhouse with a thermal curtain, the average dew point temperature measured in the vertical direction was 10.1 °C at 2 m (NS_1-T), 10.0 °C at 4 m (NS_2-T) and 8.7 °C at 5.7 m (NS_3-T). In the greenhouse without a thermal curtain, the values were 6.7 °C at 2 m (NS_4-T), 6.0 °C at 4 m (NS_5-T) and 5.9 °C at 5.7 m (NS_6-T) (Figure 5a,b). Even though the internal temperatures in the greenhouse are above the dew point temperatures, the low dew point temperatures in the roof area should be checked regularly. Otherwise, plant surfaces may become wet due to condensation and cause diseases. As a result of the statistical analyses, it was determined that the difference between the average dew point temperature in the greenhouses with and without a thermal curtain was found to be statistically significant ($p < 0.01$). Çolak [45] reported that the dew problem in greenhouses usually occurs at night, and the dew temperature values at night were higher than during the day. In the middle of the block, where the plant density was high, the average nighttime dew temperature reached 13.8 °C. Considering that the average nighttime temperatures in these regions drop to 12.0 °C, there was a dew problem reported in the greenhouse, and heating was required to prevent this. Also, placing the heating system close to the soil surface would make it easier to heat the plant due to the rise of the heated air. This study determined that the indoor temperature did not fall below the dew point due to the correct design of the heating system on the side walls and the floor. In addition, the heating pipes used to reduce the snow load on the roof also increased the temperatures in the roof area and reduced condensation. Researchers have reported that condensation occurs on the leaf surface and increases the risk of plant diseases when the leaf temperature drops below the dew point temperature at night in the greenhouse [46–48]. The study determined that vegetation heating applied to tomato plant rows in greenhouses is essential in preventing moisture condensation on plant leaves.

3.3. Comparison of Some Parameters Related to Fuel Consumption in Greenhouses

In the present study, when the indoor temperatures were kept at 15 °C in both greenhouses, fuel consumption, heat energy consumption, the overall heat transfer coefficient, the equivalent of the amount of CO_2 released into the atmosphere and fuel cost were determined. Fuel consumption was considered a function of the indoor and outdoor air temperature differences with and without thermal curtains. The temperature difference (ΔT) reached, depending on the amount of fuel consumed in the greenhouses, is given in Figure 6 for the experimental greenhouses.

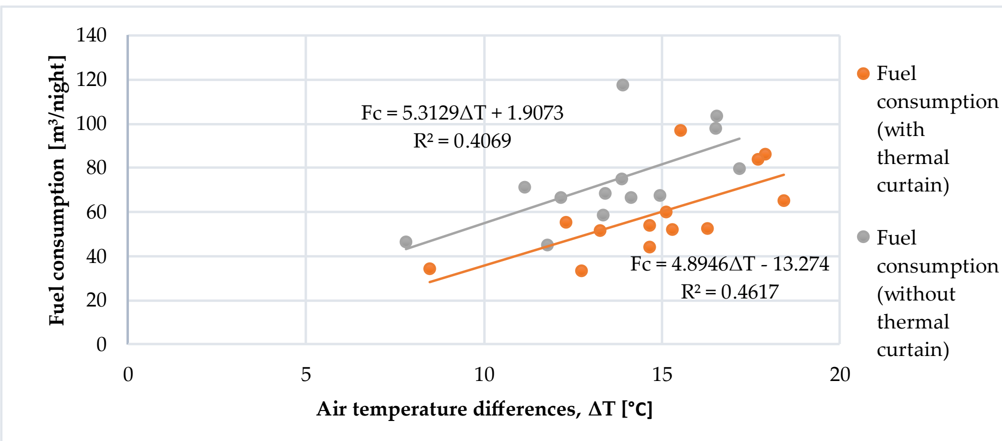


Figure 6. The temperature difference reached depending on the amount of fuel consumed in the greenhouses with and without thermal curtain.

In the greenhouse with a thermal curtain, the average nightly fuel consumed was 59.14 $m^3 \cdot night^{-1}$. In the greenhouse without a thermal curtain, the average amount of fuel consumed nightly was 74.11 $m^3 \cdot night^{-1}$. When Figure 6 is examined, it is seen that the amount of fuel consumed increases linearly depending on the increasing temperature difference. The average difference between the with-curtain and without-curtain greenhouses was 14.97 $m^3 \cdot night^{-1}$. It was determined that if the thermal curtain was closed at night times in the greenhouse where the research was conducted, 21% of the fuel could be saved. As a result of the statistical analyses, it was determined that the difference between the average fuel consumption in the greenhouses with and without a thermal curtain was found to be statistically significant ($p < 0.01$). Teitel et al. [25] reported that fuel consumption depends almost entirely on ΔT and is almost independent of heat loss due to radiation. Their study found a relationship between ΔT and fuel consumption of $R^2 = 0.50$ in the greenhouse with a heat curtain and $R^2 = 0.46$ in the greenhouse without a heat curtain. At the same time, they reported that the ratio between the curtain area and the cover area is 0.45. However, in a large commercial greenhouse where the ratio between the curtain area and the cover area is close to one, the contribution of the thermal curtain to energy savings will be more significant. Kittas et al. [26] reported energy savings of about 15% with a 65%-aluminised thermal screen and indicated that that was a rather low value that could be attributed to screen wear and the small size of their greenhouse. Accordingly, in this study, the ratio of curtain surface area to cover surface area is 0.35. It was determined that this rate was below the research's reported value. Accordingly, to increase the curtain surface area in the greenhouse and prevent heat losses, the side wall surface areas must be closed with curtains. The study by Andersson [49] reported that energy consumption is related to the temperature between indoor and outdoor temperatures and solar radiation, with the highest energy consumption at night, morning and afternoon. Von Zabeltitz [21] and Baytorun [22] state that, since all of the heat energy required for heating in temperate climates and 70–75% of it in cold regions is needed at night, significant heat savings can be achieved when the system is well designed with thermal curtains and the material is chosen well. This research determined that 80.5% of the heat energy required for heating is needed during the hours when the curtains are closed. For this reason, thermal curtains are essential to reduce heat energy consumption and increase heat savings during the night when the radiation value decreases.

Heat energy consumption was considered as a function of the indoor and outdoor air temperature differences with and without thermal curtains (Figure 7). Considering the heat energy consumption on the research days, the nightly average heat energy requirement of 453.7 $kWh \cdot night^{-1}$ was determined in the greenhouse with a thermal curtain. A nightly average heat energy requirement of 568.6 $kWh \cdot night^{-1}$ was determined in the greenhouse without a thermal curtain. The average difference between the with-curtain and without-curtain greenhouses was 114.90 $kWh \cdot night^{-1}$. If the thermal curtain were closed in the greenhouse where the research was conducted, 21% of the energy could be saved. As a result of the statistical analyses, it was determined that the difference between the average heat energy consumption in the greenhouses with and without a thermal curtain was found to be statistically significant ($p < 0.01$). Bailey [50] reported that 28% savings could be achieved in a single-layer glass-covered greenhouse with an aluminium strip thermal curtain. Öztürk and Başçetinçelik [39] reported that the effectiveness of thermal curtains was 16% and 19.8% for PE and polyester curtains, respectively. Kim et al. [18] found that curtains were an effective method to promote energy savings. Using thermal curtains in greenhouses at night can provide energy savings of 28.7% in greenhouses with and without curtains. Shakir and Farhan [51] successfully saved 21.7% of heat with different thermal curtains. Le Quillec et al. [52] reported that 22–27% savings can be achieved with thermal curtains. Previously, many researchers reported that 20–70% savings could be achieved in their studies on this subject [23,27,31,53–59]. In greenhouse cultivation, heat energy savings are one of the most important challenges, as heating costs exceed 40% of the total production cost [14]. The study determined that the 20.2% energy savings provided by the thermal curtain and the reduction in the heating costs required for tomato production are important for economical production. However, these savings rates vary depending on factors such as greenhouse structure, cover material, impermeability and wind speed. The finding of 20.2% in this study was close to similar studies in the literature. However, Önder and Baytorun [60] reported that, to achieve the expected heat increase from thermal curtains, the curtain must be well insulated with covering material, especially on the side and front facades. It was determined that it was essential to close the side and front facades with curtains in order to increase the saving rate in the researched greenhouse.

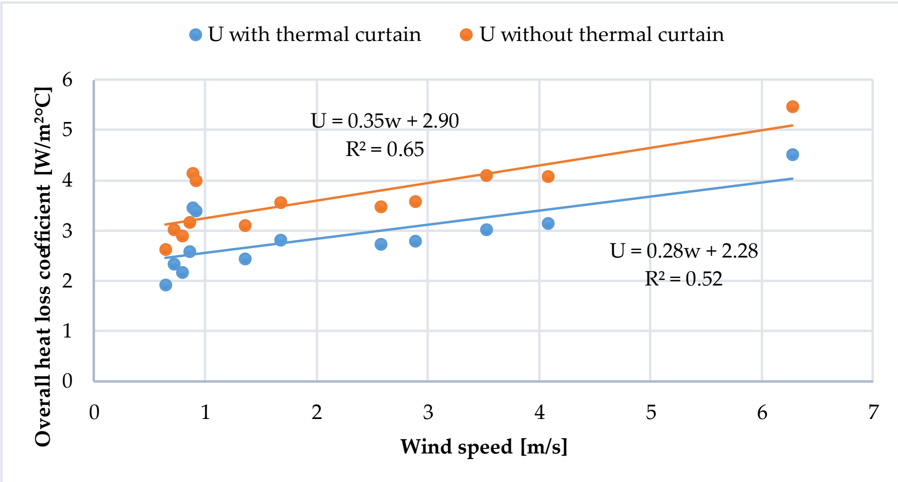


Figure 7. The relationship between overall heat transfer coefficient and wind speed of the greenhouses with and without thermal curtain.

The relationship between the average total heat transfer coefficient (U) and the outdoor wind speed (w) is given in Figure 7, which shows that the average U value increased with the increase in outdoor wind speed. This finding agreed with those of previous studies [39,61].

In the greenhouse with a thermal curtain, the relationship between the U value and wind speed (w, m·s^{-1}) was determined as U = 2.28 + 0.28v (R^2 = 0.52). In the greenhouse without a thermal curtain, it was determined as U = 2.90 + 0.35v (R^2 = 0.65). The average U value for the greenhouse without a curtain was high due to more heat loss. From the derived relationship for U obtained in the present study, [62] determined U = 2.46 W·m^{-2} °C for 4 m·s^{-1} under clear sky conditions and U = 2.38 W·m^{-2} °C under cloudy conditions. Tantau [63] determined U as 2.56 W·m^{-2} °C. Önder and Baytorun [60] determined the total heat requirement coefficient as 7.3 W·m^{-2} °C for a glass greenhouse without a thermal curtain. It was calculated as 2.8 W·m^{-2} °C in a glass greenhouse under the conditions where the thermal curtain was closed. In addition, it was reported that the total heat requirement coefficient was calculated as low in a glass greenhouse with an asymmetrical structure in which the research was conducted since the volume under the curtain is very small. Tantau [63] reported that the overall heat transfer coefficient (Ucs) includes various heat transfer parameters, such as cover material, wind speed, cloud cover, heating system and the resulting latent heat flux and evaporation-transpiration of the plant. The average U values with and without thermal curtains were 2.87 and 3.63 W·m^{-2} °C from Equation (2), respectively. Regarding the direct effects of the U values, greenhouse energy consumption decreased by 151.1 kWh when the U values decreased by 1 W·m^{-2} °C. This finding showed that the thermal energy consumption in greenhouses depends on the U value, and installing thermal curtains at night was important to promote heating savings. At the same time, it was seen that the results obtained were close to the results of the previous researchers. In the greenhouse where the research was conducted, the heat transfer coefficient decreased by 21% if the thermal curtain was closed at night. As a result of the statistical analyses, it was determined that the difference between the heat transfer coefficient in the greenhouses with and without a thermal curtain was statistically significant ($p < 0.01$).

The cost of fossil energy sources used in greenhouses and the carbon dioxide emissions they release into the atmosphere are different. This study determined the amount of CO_2 emissions released into the atmosphere when using a thermal curtain in greenhouses heated with natural gas as 116.6 kg·night^{-1}. The amount of CO_2 released to the atmosphere due to increased fuel use in the greenhouse without a thermal curtain was determined to be 146.1 kg·night^{-1}. The average difference between the with-curtain and without-curtain greenhouses was calculated as 29.5 kg·night^{-1}. In the greenhouse where the research was conducted, if the thermal curtain was closed at night, the amount of CO_2 released into the atmosphere decreased by 21%. As a result of the statistical analyses, it was determined that the difference between the average amount of CO_2 released to the atmosphere in the greenhouses with and without a thermal curtain was statistically significant ($p < 0.01$). The disadvantage of fossil energy sources used in greenhouse heating is the CO_2 emissions they release into the atmosphere. CO_2 increases the greenhouse effect that causes global warming [22]. Agriculture is one of the factors that play a significant role in CO_2 emissions [64–66]. The continued use of fossil fuels is contributing to severe environmental pollution and the establishment of an abnormal climate [67]. Boyacı [68] stated that if natural gas is used as fuel, less carbon dioxide emissions will be released into the atmosphere than imported coal and heating fuel. Accordingly, in the case of using a thermal curtain, the amount of CO_2 released to the atmosphere decreased by 21% with the decreasing energy requirement.

In the last few years, energy consumption in greenhouses has gained increased interest due to the liberalisation of the energy market and the increasing prices of natural gas [69]. Due to today's continuous increase in energy costs, greenhouse insulation and minimising heating requirements are equally as important as heating itself [70]. Reducing heating costs is a major challenge for greenhouse growers, especially those in cold regions [71]. Tezcan and Büyüktaş [72] reported that greenhouses can be heated with natural gas at the lowest cost. In this study, the nightly average fuel cost (1 m^3 = USD 0.36) was determined to be USD 21.3 for the greenhouse with a thermal curtain, while it was USD 26.7 for the greenhouse without a thermal curtain. The average difference between with-curtain and without-curtain greenhouses was calculated as USD 5.4. In the greenhouse where the research was conducted, if the thermal curtain was closed at night, the fuel cost decreased by 21%. As a result of the statistical analyses, it was determined that the difference between the average fuel cost in the greenhouses with and without a thermal curtain was statistically significant ($p < 0.01$). If a thermal curtain is used, a reduction in the share of heating in production costs will be possible. In a greenhouse where 50 kg·m^{-2} tomatoes are produced per unit area, the heating cost for one kg of tomatoes is USD 0.43·kg^{-1} if a thermal curtain is used, while it is USD 0.54· kg^{-1} in a greenhouse without a thermal curtain. In this case, the share of heating in the production costs in the greenhouse with the heat curtain decreased by 21%. At the same time, the amount of CO_2 released into the atmosphere will decrease thanks to the reduced energy requirement.

4. Conclusions

Energy conservation in heated greenhouses is as essential as heating in greenhouses. Constantly increasing energy prices have led greenhouse producers to seek energy efficiency. A thermal curtain is one of the most commonly used technical measures to increase energy efficiency in greenhouses. In greenhouses with and without a curtain, the temperature, relative humidity and dew point temperature values were measured to determine the effects of the indoor thermal curtain on these indoor climate parameters. In addition, the effects of the thermal curtain on the heat transfer coefficient, fuel consumption and energy savings were determined. According to the present results, the following concluding remarks were obtained:

1. Of the heat energy required for heating, 80.5% was needed during the hours when the curtain was closed.
2. In the greenhouse with a thermal curtain, fuel consumption was 59.14 $m^3 \cdot night^{-1}$, and it was 74.11 $m^3 \cdot night^{-1}$ without a thermal curtain. At the same time, the heat energy consumption was 453.7 $kWh \cdot night^{-1}$ in the greenhouse with a thermal curtain and 568.6 $kWh \cdot night^{-1}$ without a thermal curtain.
3. The heating cost of one kg of tomatoes in a greenhouse without a thermal curtain is USD 0.11 higher, depending on the fuel consumed.
4. The heat energy savings with a thermal curtain were 21% on average (14.4–26.4%).
5. The average heat transfer coefficient was calculated as U = 2.87 $W \cdot m^{-2}$ °C in the greenhouse with a curtain and as U = 3.63 $W \cdot m^{-2}$ °C in the greenhouse without a curtain. Accordingly, it has been determined that the energy consumption will decrease by 151.1 kWh if the U value decreases by 1 $W \cdot m^{-2}$ °C.
6. In the case of a thermal curtain, the CO_2 emissions released into the atmosphere were 29.5 $kg \cdot night^{-1}$ less than without a thermal curtain.
7. The nightly average fuel cost in the greenhouse with a thermal curtain was USD 5.4$\cdot night^{-1}$ cheaper than without a thermal curtain.

To conclude, it has been determined that using heat curtains is important in regulating the indoor climate in greenhouses where off-season farming is carried out, reducing the share of heating in production costs and contributing to economical and environmentally friendly production by reducing CO_2 released into the atmosphere.

Author Contributions: Conceptualization, S.B. and A.A.; methodology, S.B. and A.A.; validation, S.B., R.R. and B.J.; formal analysis, S.B.; investigation, S.B.; resources, S.B. and A.A.; data curation, S.B. and A.A.; writing—original draft preparation, S.B., A.A. and J.K.; writing—review and editing, J.K., D.L. and A.A.; visualization, S.B. and J.K.; supervision, R.R., D.L. and B.J.; project administration, S.B. and A.A.; funding acquisition, A.A. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: Data are contained within the article.

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

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