The effect of CO₂ enrichment in a closed greenhouse equipped with NIR-reflecting film and EHP cooling on the yield and quality of tomato fruits during the summer season

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Abstract

We investigated the combined influence of cooling using electric heat pumps and CO₂ enrichment in a closed greenhouse equipped with a near infrared solar radiation (NIR)-reflecting film on the yield and quality of tomato fruits during the summer season. The air temperature of the ‘Control’ greenhouse were controlled through conventional natural ventilation windows, shading curtains and a fog cooling system. The air temperature of the ‘Closed’ greenhouse were controlled by cooling of electric heat pumps and a NIR-reflecting film curtain. The CO₂ concentration was maintained at around 1000 μmol mol⁻¹ in the Closed greenhouse. During the experiment period when the outside temperature of the greenhouses was relatively high, the mean daytime air temperature was cooler by more than 3 °C in the Closed greenhouse than that in the Control. The total dry weight of the tomato plants and fruit yield per plant at the end of the experiment was significantly higher in the Closed greenhouse compared to the Control. The result indicated that the improved yield and quality of the Closed greenhouse resulted from the air temperature being controlled within the optimal range for growth and the subsequent increased rates of fruit maturation and photosynthesis due to CO₂ enrichment.

Key words: Air temperature, CO₂ gas supply, Controlled environment, Fog cooling, Photosynthetically active radiation

1. Introduction

CO₂ enrichment is a method used to promote the growth of plants. Many reports have shown that the total yield and average fruit weight of cucumber and tomato crops are increased by supplying CO₂ gas during cultivation (Kimball et al., 1979; Nilsen et al., 1983; Sánchez et al., 2005). In addition, a previous study reported that the amount of total sugar was increased by CO₂ enrichment (Islam et al., 1994). In general, CO₂ enrichment is conducted when the greenhouse ventilation windows are closed because most of the supplied CO₂ would otherwise escape through the open ventilation windows. Therefore, in general, CO₂ enrichment is not carried out during the high temperature period with high solar radiation because the ventilation windows need to remain open. CO₂ enrichment is instead often carried out in the mornings and evenings during autumn and winter, when the ventilation windows can remain closed without adverse effects on the crop (Loslovich et al., 1995). However, Mortensen (1987) reported that CO₂ enrichment in the mornings, evenings, and on cloudy days did not effectively increase plant growth because the available CO₂ remained in excess due to the low availability of solar radiation for photosynthesis.

In the Netherlands, closed greenhouse systems have been developed (Heuvelink et al., 2008). Cooling by ventilation is replaced partly (in semi-closed greenhouses) or completely (in closed greenhouses) by mechanical cooling (De Gelder et al., 2012). Closed greenhouses can maintain a high CO₂ concentration throughout a year because ventilation windows are kept closed, even in summer (Heuvelink et al., 2008). CO₂ enriched, closed greenhouses have been shown to have higher yields compared to those without CO₂ enrichment (Heuvelink et al., 2008; Qian et al., 2011).

CO₂ enriched, closed greenhouses that are constructed in high annual solar radiation areas, such as Japan, are expected to greatly promote plant growth and increase yield. However, air temperatures inside greenhouses can rise to very high levels due to the abundance of solar radiation, and thus increase the required cooling load. Several cooling methods are used in greenhouses. Although the evaporative cooling method, e.g., fog cooling, is effective in other instances, this method is impractical for use in closed greenhouses due to the resultant high relative humidity. Other cooling methods are, therefore, required different, e.g., the use of electric heat pumps (EHPs). Furthermore, the cooling load can be reduced by shading, e.g., with shading curtains.

In general, a shading curtain maintains a solar radiation transmittance that is nearly constant regardless of wavelength, i.e., it has a low transmittance of photosynthetically active radiation (PAR) and near infrared solar radiation (NIR). Although, NIR-filtering multilayer coatings applied to outer shading materials are used as shading material, they also reduce the transmittance of PAR as do shading curtains (Hemming et al., 2006). Recently, a NIR-reflecting film with a high transmittance of PAR and a low transmittance of NIR was developed for agricultural applications.
In a previous study, we reported that shading inside a greenhouse by NIR-reflecting film caused a decrease in leaf temperature and promoted plant growth (Ishigami et al., 2014). We also clarified that the newly developed NIR reflecting film was able to decrease the air temperature by 2 °C during the high temperature period (unpublished). Therefore, we demonstrated the possibility of reducing the cooling load without suppressing plant growth by using NIR-reflecting film. From the above, it can be expected that CO₂ enrichment during the summer season will be effective if EHP cooling is used. However, there are no known reports that have investigated the combined influence of cooling using EHPs and CO₂ enrichment equipped with an NIR reflecting film on crop yield and the quality of fruits.

Therefore, in this study, we investigated the effects of cooling using EHPs and CO₂ enrichment in a closed greenhouse system equipped with NIR-reflecting film on the yield and quality of tomato fruits.

2. Materials and Methods

2.1 Test greenhouses

Greenhouses (labelled A and B) of the single ridge gabled roof type, made of plastic, and constructed in the Matsudo campus of the Chiba University were used as the test greenhouses (8 × 18 × 4 m; width × length × average height). The floor area of each greenhouse was 144 m². Fluorine-based film was used as the covering material for the roof surface and the gable side, and polyolefin-based film (designed for agricultural applications) was used as the covering material for the sides. The greenhouses had roof windows and side windows as the ventilation windows. These windows were protected with 0.4 mm anti-insect screens.

Greenhouse A, in which environmental conditions were controlled through conventional natural ventilation windows, was used as the control. The ventilation windows, shading curtains and a fog cooling system in the greenhouse were controlled by an integrated environmental control system (Profarm controller, Toyotane Co., Ltd.). The CO₂ enrichment was not conducted in greenhouse A, which is hereafter referred to as the ‘Control’ system.

Greenhouse B, with closed ventilation windows, was used as the closed greenhouse. The test greenhouse conditions, i.e., ventilation windows, EHPs, and CO₂ enrichment, were controlled by a ubiquitous environmental control system (UECS, Holt plan LLC.). The greenhouse had three EHPs. One of the EHPs (NGP104T, NEPON Inc. (Heat pump A; HP A)) had a cooling ability of 22.0 kW. The other two EHPs (NGP1010TX, NEPON Inc. (Heat pump B and C; HP B and HP C)) each had a cooling ability of 25.0 kW. HP A could control the output, i.e., off and on. HPs B and C could control the output more specifically, i.e., on, off, low, and high outputs. CO₂ enrichment was conducted using liquefied CO₂ gas. Two circulation fans were installed to equalize CO₂ concentration inside the greenhouse. The circulation fans remained active throughout the treatments. Greenhouse B is hereafter referred to as the ‘Closed’ system.

2.2 Shading material

The newly developed NIR-reflecting film for agricultural application (Prototype Teijin Film Solutions, Ltd.) was used as the shading material in the Closed system. This shading curtain had a low NIR transmittance by selectively reflecting wavelengths of 800–1100 nm (Fig. 1) and PAR and NIR transmittances of 86% and 45%, respectively. The film was installed at a height of ~3 m from the ground. This shading curtain was always closed during the experiment. Agricultural polyolefin film (PAR transmittance: 90%) was overlaid on the covering material of the Control greenhouse roof to ensure that the total PAR transmittance of the two test greenhouses was almost the same.

2.3 Measurement of the environmental conditions inside the test greenhouses

Air temperature and relative humidity were measured inside the greenhouses using meteorological sensors. Solar radiation inside each greenhouse was measured at a height of ~2 m from the ground, using a pyranometer (MS-100, EKO INSTRUMENTS Co., Ltd.). Photosynthetic photon flux density (PPFD) was also measured using a light quantum meter (ML-020P, EKO INSTRUMENTS Co., Ltd.), which was set next to the pyranometer.

![Fig. 1. Transmittance and spectral distribution of the near infrared solar radiation (NIR)-reflecting film under sunlight. The value of the spectral irradiance was shown as a relative value when the maximum value of the sunlight was 1.0. Spectral irradiance of the NIR-reflecting film was calculated by multiplying spectral irradiance of the sunlight and transmittance of the shading curtain. PAR, photosynthetically active radiation.](image-url)
2.4 Control conditions

Environmental control conditions of each treatment are shown in Table 1. The study was conducted from July 12 to October 20, 2017. Fog cooling was conducted during the daytime in the Control when the greenhouse air temperature exceeded 27.0 °C and the greenhouse relative humidity dropped below 80%. In the Closed system, cooling was performed by using the EHPs to change cooling capacity during the daytime in the four steps described below.

i) Air temperature was maintained at above 27.0 °C: all three heat pumps were operated at 100% of output.

ii) Air temperature was maintained between 26.0 and 27.0 °C: HPs B and C were operated at 100% of output.

iii) Air temperature was maintained between 25.5 and 26.0 °C: HPs B and C were operated at 50% of output.

iv) Air temperature was lower than 25.5 °C: all three heat pumps were turned off.

2.5 Cultivation outline

Tomato plants (*Solanum lycopersicum* L., cv. ‘Reika’, Sakata Seed Corporation) were used as the test plants. Tomato seeds were sown in culture soil (Napura mixing soil type S, Yanmar Co., Ltd.) on June 7, 2017 and kept in the dark in an incubator (MIR-553, Panasonic Corporation) for three days, and then transferred to the environmental conditions, i.e., air temperatures of 26 °C / 20 °C (daytime/nighttime), and a 16 h d^−1 light period. The tomato seedlings were irrigated with water for 6 days after sowing (DAS) and then irrigated with nutrient solution (OAT Agrio Co., Ltd., 1/2 unit) from 7 DAS. At 23 DAS, the seedlings were transplanted to rock wool cubes (DELT6.5G Grodan, Roermond, The Netherlands) and allowed to develop for 12 days in the greenhouse. The tomato plants were settled planted in rock wool slabs (2075 A2W, Grodan, Roermond, The Netherlands) that were placed on the cultivation beds. The experiment commenced at 35 DAS. After settled planting, each slab was irrigated with nutrient solution (OAT Agrio Co., Ltd., 1 unit) by drip tubes. The water irrigation increased from 0.75 L per plant at the start of the experiment to 1.5 L per plant at the end of the experiment.

2.6 Growth measurements

Growth measurements (fresh weight, dry weight, plant height, leaf area) were collected every 20 days. The yield was investigated separately for each truss. The fruits were harvested from the fourth truss. Brix and acidity were measured using a Brix meter (Fruit selector, Kubota Corporation). The fruit cracking ratio and blossom-end rot ratio were calculated by dividing the number of cracked fruit or rotten blossom ends, respectively, by the total number of fruits. In addition, the marketable fruit ratio was calculated by subtracting fruit cracking ratio and blossom-end rot ratio from one.

3. Results and Discussion

3.1 Environmental conditions inside the greenhouses

The mean air temperatures inside the greenhouses from 06:00 to 18:00 on a sunny day with a maximum air temperature outside the greenhouse of 35.3 °C (August 24) were 31.0 °C and 27.1 °C in the Control and Closed systems, respectively (Fig. 2). The mean air temperatures inside the greenhouses from the start of the test (July 12) to October 20 were 26.5 °C and 25.8 °C in the Control and Closed systems, respectively. When the outside air temperatures were relatively high i.e., from July 12 to August 31, the mean air temperatures inside the greenhouses were 29.4 °C and 26.2 °C in the Control and Closed, respectively. In addition, the mean air temperatures inside the greenhouses from September 1 to the end of the test (October 20) were

![Fig. 2. Temporal air temperature changes outside and inside the greenhouses (Control and Closed) on August 24, 2017.](image)

![Fig. 3. Daily mean daytime air temperature variations in the Control and Closed greenhouses from July 12 to October 20, 2017.](image)
23.5 °C and 23.6 °C in the Control and Closed, respectively. During the daytime, the mean air temperature in the Control was higher than that in Closed system because the fog cooling stopped when the relative humidity exceeded the set point (80%), whereas the EHPs in the Closed system operated to maintain the air temperature at a set value (Fig. 3).

Less solar radiation was measured inside the Closed greenhouse than in the Control (Fig. 4). In addition, there was less PPFD inside the Closed greenhouse than in the Control (Fig. 5), i.e., the integrated PPFD was 81% of that measured in the Control. The proportions of PPFD were maintained at higher levels than that of solar radiation, i.e., the integrated solar radiation in the Closed system was 60% that of the Control.

During the daytime, the mean CO₂ concentrations inside the greenhouses were 407 µmol mol⁻¹ and 1041 µmol mol⁻¹ in the Control and Closed systems, respectively. The CO₂ concentration in the Closed system was approximately controlled at this set point.

### 3.2 Growth and yield

After 20 days of treatment, the total dry weights of the tomato plants in the Closed system were significantly larger than those in the Control (Fig. 6). The yield at each truss was significantly higher in the Closed system than that in Control (Fig. 7). The ripening fruit yields per plant from the first to the fourth trusses were significantly larger in the Closed system (1.88 kg) than that in the Control (1.11 kg). In addition, the immature fruit yields per plant from the fifth to the tenth trusses were larger in the Closed system (2.16 kg) than that in the Control (1.53 kg). The difference between Control and Closed in total yield including immature fruit was 1.4 kg.

In the first to fourth trusses, no significant differences were found in the number of flowers between the treatments. However, the number of fruits in the Closed system was significantly higher than that in the Control (Table 2). In previous studies, the number of fruits were shown to decrease when exposed to high temperature conditions during the period of differentiation and development of the flower bud (Iwahori et al., 1963). In this treatment, the mean air temperatures during the day until the flowering of the first flower in the fourth truss were higher in the Control (30.2 °C) than in the Closed system.
The fruit load in the Closed system was suppressed because the mean air temperature in the Closed greenhouse was lower than that in the Control greenhouse. Iwahori et al. (1963) also reported a yield decrease of ~50% when tomato plants were exposed to 35 °C for 3 h d⁻¹ for 5 days during the flowering stage of the first truss, compared with a 30 °C treatment. Furthermore, Rahman et al. (1998) reported that the total dry weight of the above ground plant parts decreased in tomato plants cultivated at 30 °C during the day, compared with 23 °C. In the present study, the mean air temperature from 10:00 to 14:00 for 5 days before flowering of the first truss was 33.5 °C in the Control and 28.3 °C in the Closed system, i.e., a difference of more than 5 °C. In the Closed system, the EHP cooling suppressed the excessive temperature increase in the greenhouse and maintained the temperature in a suitable range for photosynthesis. In addition, CO₂ enrichment ensured that the CO₂ concentration was maintained at around 1000 μmol mol⁻¹ in the Closed system, whereas the CO₂ concentration was 407 μmol mol⁻¹ in the Control.

The findings show that the growth of the tomatoes in the Closed system was promoted, and that the yield in the first to fourth trusses was significantly higher than that in the Control. The fruit load in the Closed system was suppressed because many fruits were dropped before harvesting due to the blossom-end rot, and the number of fruits that could be used for the calculation was as small as 11. The ratio of marketable fruit was higher in the Closed system than in the Control (Table 3).

Hussey (1965) reported that the optimal growth temperature of tomatoes during the daytime is around 25 °C. In addition, Islam et al. (1994) reported that the amount of total sugar was increased by CO₂ enrichment. According to the findings of the present study, the Brix values in the Closed system was higher than that in the Control because the air temperature in the Closed system was controlled within the optimal range for growth by cooling of the EHPs and the NIR-reflecting film. In addition, the photosynthetic rate increased due to the CO₂ enrichment. There were no significant differences in the fruit quality between the third and fourth trusses, but the Brix value showed a tendency to be higher in the Closed system than in the Control; also due to the EHP cooling and CO₂ enrichment.

### 3.3 Fruit quality

The Brix values of fruits in the first and second trusses in the Closed system were significantly higher than those in the Control. There were no significant differences in the acidity of the fruits between the Control and Closed systems. The blossom-end rot ratio of the Closed system tended to be smaller than that in the Control. The fruit cracking ratio of the Closed system was also smaller than that in the Control, except for the third truss. The fruit cracking ratio of the third truss in the Control was 0% because many fruits were dropped before harvesting due to the blossom-end rot, and the number of fruits that could be used for the calculation was as small as 11. The ratio of marketable fruit was higher in the Closed system than in the Control (Table 3).

### 3.4 Evaluation of the Closed system

Since test greenhouses were used, the capacity and performance of the fog cooling system and EHPs were much higher than in commercial models. This made it difficult to estimate the initial cost of the Closed system. Therefore, in this section, we discuss the operational running costs and fruit yield increase in the cultivation area (144 m²) during the 100-day experimental period (July 12 to October 20, 2017) in order to evaluate the technologies installed in the Closed system (Table 4).

The fog cooling system in the Control was operated for an average of 2 h daily; the fogging rate was 18.1 g m⁻² min⁻¹, using approximately 31 m³ of water during the study period. Assuming a water rate of 300 yen m⁻³, the total cost of water

### Table 2. Numbers of flowers and fruits of the first to forth tomato trusses in the Control and Closed greenhouses.

| Truss | Treatment | Number of flowers | Number of fruits |
|-------|-----------|-------------------|-----------------|
| First | Control   | 6.0               | 2.8*            |
|       | Closed    | 5.8               | 4.6             |
| Second| Control   | 5.2               | 3.1*            |
|       | Closed    | 5.4               | 5.1             |
| Third | Control   | 2.0               | 0.9*            |
|       | Closed    | 3.2               | 1.9             |
| Fourth| Control   | 3.6               | 1.3*            |
|       | Closed    | 3.4               | 2.6             |

* indicates significant differences at the P < 0.05 level (T-test) among the treatments in the same truss. Number of samples were 12 in first, second, and third trusses. Number of samples was 8 in fourth truss.

### Table 3. Quality of fruits on the first to fourth tomato trusses in the Control and Closed greenhouses.

| Truss | Treatment | Brix¹ (%) | Acidity¹ (%) | Blossom-end rot ratio | Fruit cracking ratio | Marketable fruit ratio |
|-------|-----------|-----------|--------------|-----------------------|----------------------|------------------------|
| 1st   | Control   | 5.9       | 0.39         | 0.35                  | 0.11                 | 0.54                   |
|       | Closed    | 6.5       | 0.40         | 0.14                  | 0.06                 | 0.80                   |
| 2nd   | Control   | 5.7       | 0.35         | 0.20                  | 0.08                 | 0.72                   |
|       | Closed    | 6.1       | 0.36         | 0.13                  | 0.05                 | 0.82                   |
| 3rd   | Control   | 5.5       | 0.27         | 0.36                  | 0.00                 | 0.64                   |
|       | Closed    | 5.6       | 0.28         | 0.22                  | 0.06                 | 0.72                   |
| 4th   | Control   | 5.9       | 0.32         | 0.10                  | 0.10                 | 0.80                   |
|       | Closed    | 6.0       | 0.32         | 0.10                  | 0.10                 | 0.80                   |

¹ indicates mean of 10 fruits.

* indicates significant differences at the P < 0.05 level (T-test) among the treatments in the same truss.
Table 4. Comparison of the cost of energy and resources used for environmental control between the Control and Closed greenhouses throughout the experimental period.

| Setting Parameters      | Systems     | Energy       | Amount       | Assumed price | Treatment cost (yen) |
|-------------------------|-------------|--------------|--------------|---------------|---------------------|
|                         | Fog cooling | Water        | 31 m²        | 300 yen m⁻²   | Control             |
|                         |             | Electricity  | 300 kWh      | 15 yen kWh⁻¹  | 9,300               |
|                         |             |              |              |               | Closed              |
|                         | EHPs        | Electricity  | 9,500 kWh    | 15 yen kWh⁻¹  | 4,500               |
| CO₂ concentration (μmol mol⁻¹) | CO₂ cylinder | CO₂ gas     | 660 kg       | 120 yen kg⁻¹  | 142,500             |
|                         |             |              |              |               |                     |
| Total running cost (a)  |             |              |              |               | 13,800              |
| Total income (b)        |             |              |              |               | 349,000             |
| Net income (b-a)        |             |              |              |               | 335,200              |

Note:
The floor area of each greenhouse: 144 m².
Planting density: 2.5 plants m⁻².
Tomato trade price: 373 yen kg⁻¹ (MAFF, 2018).
Total income from the Control greenhouse: 2.5 plants m⁻² × 144 m² × 2.6 kg plant⁻¹ × 373 yen kg⁻¹.
Total income from Closed greenhouses: 2.5 plants m⁻² × 144 m² × 4.0 kg plant⁻¹ × 373 yen kg⁻¹.

used was approximately 9,300 yen. The fog cooling system compressor had a total rated power of 1.5 kW. Assuming an electricity rate of 15 yen kWh⁻¹, the total cost of electricity used was approximately 4,500 yen. The total running cost associated with the Control was therefore approximately 13,800 yen. In the Closed system, the total electric consumption of the three EHPs was 9,500 kWh, at a total cost of approximately 142,500 yen. Approximately 660 kg of liquefied CO₂ gas was used for CO₂ enrichment. Assuming a CO₂ price of 120 yen kg⁻¹ (NILIM, 2016), the total CO₂ cost was approximately 79,200 yen. Therefore, the total running cost of the Closed system was approximately 221,700 yen, which was 207,900 yen higher than the Control system.

The total yield of ripening and immature fruits per plant was 2.6 kg and 4.0 kg in the Control and Closed system, respectively, as described in section 3.2. Assuming a planting density of 2.5 plants m⁻², as is standard in commercial greenhouses (Hisaeda and Nishina, 2007), then 360 plants can be cultivated in the cultivation area. In this case, a Closed system can provide an increase in total yield of approximately 504 kg and, based on a tomato trade price of 373 yen kg⁻¹ (MAFF, 2018), increased income of approximately 188,000 yen.

However, the higher running costs of the Closed system means it yields an overall decrease in income of approximately 19,900 yen. Income would be further significantly decreased if the initial cost of setting up the Closed system is taken into account.

However, there are several advantages to producing tomato in a Closed system. The total dry weight of the tomato plants was significantly higher in the Closed than Control system, and the former also produced larger immature fruit yields per plant from the fifth to tenth trusses. Therefore, the yield of marketable fruits after the summer period should increase in a Closed system. Smaller quantities of agrichemicals were used in the Closed system, but damage from disease and insects was relatively low compared with the Control. Thus, lower costs and spraying frequency of agricultural chemicals are associated with a Closed system.

There may be locations where electricity and/or CO₂ prices are relatively cheap, not only in Japan but also globally. Therefore, further improvement of the technologies and cultivation management necessary in a Closed system, so that they are less resource-intensive, can facilitate its commercialization by taking advantage of the availability of cheaper inputs. In order to achieve such commercialization, the following are considered to be examples of key areas of research: i) the development of covering material with a higher NIR reflectivity to reduce the cooling load; ii) the development of a CO₂ enrichment method that is responsive to solar radiation intensity, and increases the photosynthetic rate of plants by minimizing CO₂ supply; and iii) local cooling of plants to reduce EHP operation.

4. Conclusion

During a period when the outside temperature of the greenhouses was relatively high, the mean daytime air temperature was cooler by more than 3 °C in the Closed greenhouse than that in the Control. The mean air temperature in the Closed greenhouse was controlled to the optimum growth temperature of tomatoes. In addition, the CO₂ concentration was maintained at around 1000 μmol mol⁻¹ in the Closed system due to CO₂ enrichment, whereas the CO₂ concentration was 407 μmol mol⁻¹ in the Control.

As a result, the total dry weight of the tomato plants in the Closed system was significantly higher than that in the Control at each measurement after 20 days of treatment, and the fruit yield per plant at the end of the experiment was ~60% higher in the Closed system compared to the Control. In addition, the Brix values of the first and second trusses in the Closed system were significantly higher than those in the Control. The marketable fruit ratio was also higher in the Closed system than in the Control.

Collectively, the findings of the present study indicated that the fruit yield and quality of tomatoes grown in the Closed greenhouse conditions were higher than those in the Control. The improved yield and quality of the Closed system resulted from the air temperature being controlled within the optimal range for
growth and the subsequent increased rates of fruit maturation and photosynthesis due to CO₂ enrichment.

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