Invited Review

Local Temperature Control in Greenhouse Vegetable Production

Yasushi Kawasaki* and Yuki Yoneda

Western Region Agricultural Research Center, NARO, Zentsuji 765-8508, Japan

Uniform temperature throughout a greenhouse is recommended, as the present climate control method and many other studies have shown that the temperature gradient decreases vertically and horizontally in a greenhouse. However, recent research revealed that roots, fruits, flowers, and shoot-tips are more sensitive to temperature changes than leaves and stems, indicating that uniform temperature control may not be necessary. In addition, energy-saving techniques that do not lead to yield loss are desirable to reduce energy costs and ensure sustainable greenhouse production. In this paper, we review current studies on local temperature control methods in greenhouse vegetable production, primarily focusing on the tomato, and compare them with novel climate-control techniques. Roots, fruits, shoot-tips and flowers are sensitive to temperature changes, showing negative symptoms under extreme temperature conditions. Therefore, the temperature of these plant organs should be controlled locally. Root zone temperature control enhances root growth and its associated physiological activities, promoting uptake of water and mineral nutrients. This subsequently leads to enhanced growth of shoots. Fruit temperature control may not be effective for tomato plants, but it promotes fruit growth and fruit sugar accumulation in melons and watermelons. Shoot-tip temperature control promotes the differentiation of leaf and flower buds. Flower temperature control enhances pollen viability and promotes fruit set. The combination of shoot-tip and flower heating enables low energy consumption compared with conventional heating, without loss of yield. Local temperature control techniques (except roots) have been studied in recent years; however, there is a distinct lack of research on the physiological mechanisms and practical approaches to develop a better local temperature control system. Thus, further studies are required on this area in the future.

Key Words: energy saving, fruit temperature, root-zone temperature, shoot-tip temperature, temperature distribution.

Introduction

In greenhouse vegetable production, temperature can be controlled easily compared with production in open fields. Using greenhouses with thermal screen and heating systems is important in securing winter vegetable production. Additionally, in recent years, greenhouses have been using cooling systems for summer production, which enable year-round greenhouse production. These techniques are effective for maximizing employee utility and ensuring the best possible productivity in greenhouses because high temperatures in summer often interrupt vegetable production in some regions. Since temperature control techniques are costly, it is important to research ways in which costs can be minimized and the effects of temperature control can be maximized. Reducing energy expenditure simultaneously reduces carbon dioxide emissions and contributes to sustainable vegetable production.

The study of temperature control in greenhouses started in the 1940s (Went, 1943, 1944). After that, more studies followed, and the optimum temperature for plant growth and the temperatures at which high and low temperature injury occur were also demonstrated. Tomato plants (Solanum lycopersicum L.), for example, grow well at a daily mean temperature of 15–25°C, but are damaged under suboptimal temperature conditions, differing according to cultivar and other environmental conditions such as solar radiation (Table 1). Flowers (Peet et al., 1997; Sato et al., 2000, 2002) are the most temperature-sensitive organs in tomato plants, followed by roots (Gosselin and Trudel, 1983a, b), shoot-tips (Grimstad and Frimanslund, 1993) and developing fruits (Adams and Valdés, 2002; Adams et al., 2001;
Bertin, 2005), which are also relatively sensitive. On the other hand, severe injuries to the leaves and stems rarely occur earlier than those in the other organs.

Horizontal and vertical temperature differences in greenhouses should be reduced and many temperature control methods have been tested to achieve a uniform temperature by changing the position of the heating pipes or by using a circulator (Fernandez and Bailey, 1994; Jeff and Jones, 1973; Kuroyanagi, 2016; Teitel and Tanny, 1998). However, having a temperature is not absolutely essential for adequate plant growth, as roots and flowers (the most temperature-sensitive organs) only occupy a small space in the greenhouse. Therefore, local temperature control techniques based on the physiological temperature responses of each plant organ, are important to ensure adequate plant growth. These are novel temperature control techniques, by which temperature-sensitive organs are controlled aggressively, whereas non-temperature-sensitive organs do not need to be controlled aggressively. Since these techniques do not require temperature control uniformly throughout the entire greenhouse, reduced energy expenditure can be expected. In addition, less temperature injury will occur as these techniques ensure that temperature-sensitive organs are maintained at an optimal temperature.

Cooling is used as temperature control in the summer, using fogging (Handarto et al., 2006, 2007) and fan-and-pad (Al-Mulla et al., 2018; Lopez et al., 2010) systems. These systems operate with low energy costs as they use heat from water vaporization, but they have more difficulty to control temperature and humidity adequately. Although heat-pumps are used when accurate temperature control is needed, their use is not recommended during the day due to the huge energy costs required. Local cooling techniques could balance between accurate temperature control and low energy costs; however, little information is available about these techniques compared to local heating techniques. Even so, studies on root-zone cooling methods have been reported and some of them are in commercial use. On the other hand, few studies on local cooling, except on the root-zone, have been reported. However, these techniques will play a more important role in the future, as

### Table 1. Partial physiological effects of temperature on tomatoes.

| Mean daily temperature (°C) | Shoot tip | Flower | Fruit | Leaf | Stem | Root |
|-----------------------------|-----------|--------|-------|------|------|------|
| ~35                         |           |        | Prevented photosynthesis (Heuvelink and Dorais, 2005) |       |
| ~30                         | Occur abnormal development (NaanDanJain, 2012) | Decrease pollen viability and fruit set (Sato et al., 2006) | Inhibited carotenoids biosynthesis (Tomes, 1963) |       | Prevented mineral absorption (Gosselin and Trudel, 1983b) |
| ~25                         | (Optimum) | (Optimum) | (Optimum) | (Optimum) | (Optimum) |       |
| ~20                         |           |        |       |      |      |      |
| ~15                         | Prevented elongation (Grimstad and Frimanslund, 1993) | Decrease pollen viability and fruit set (Charles and Harris, 1972) | Delayed growth and development (Adams et al., 2001) |       |
| ~10                         |           |        |       |      |      | Prevented photosynthesis (Heuvelink and Dorais, 2005) |

Table 1. Partial physiological effects of temperature on tomatoes.
high temperature injury is predicted to occur more frequently in low latitude areas due to the impact of global warming.

In this review, we discuss current studies on local temperature control methods in greenhouse vegetable production, primarily focused on the tomato. We also compare them with novel climate control techniques.

Local Temperature Control of Roots

Root-zone temperature conditions differ from those above-ground and the study of plant reactions to root-zone temperature has a long history (Kramer, 1934). Because root-zone temperatures can be easily distinguished from above-ground temperatures, local temperature control of the root-zone has also been studied for a long time. The oldest studies focused on mineral absorption and vegetative growth in tomato plants under various root-zone temperature conditions in greenhouses (Davis and Lingle, 1961; Lingle and Davis, 1959). Since then, many studies on root-zone temperature control have been reported, with most of these focusing on maximizing root activity and shoot growth under optimal air temperature (Fujishige et al., 1991; Gosselin and Trudel, 1982, 1983a, b, 1984, 1985; Hurewitz and Janes, 1983; Ikeda and Osawa, 1988; Kabu and Toop, 1970; Tindall et al., 1990; Yelle et al., 1987). However, few studies have investigated root-zone temperature control to save energy or to alleviate temperature injury under suboptimal air temperature conditions. When the root-zone temperature is kept at an optimal level under suboptimal air temperature conditions, the balance of plant growth regulators changes, causing enhanced root growth and activities, accelerated water and mineral nutrient uptake, enhanced shoot growth and activity (e.g., photosynthesis), and finally increased yield (Fig. 1).

An optimum root-zone temperature increases the distribution of assimilates to the roots and promotes root growth (Shishido and Kumakura, 1994). In tomato plants, root growth was promoted earlier than shoot growth when the root-zone was cooled from 33.7°C to 24.6°C under high air temperature conditions in summer (30.8°C; average daily mean temperature) (Kawasaki et al., 2013). A similar effect was observed when the root-zone was heated from 5.8°C to 16.6°C under low air temperature conditions in winter (5.9°C; average daily minimum night temperature) (Kawasaki et al., 2014). A similar effect was observed when the root-zone was heated from 5.8°C to 16.6°C under low air temperature conditions in winter (5.9°C; average daily minimum night temperature) (Kawasaki et al., 2014). A similar effect was observed when the root-zone was heated from 5.8°C to 16.6°C under low air temperature conditions in winter (5.9°C; average daily minimum night temperature) (Kawasaki et al., 2014).

In cucumber plants, heating the root-zone to 19°C from 13°C increased xylem exudation at 20/12°C (day/night) air temperature (Wang et al., 2016). Shoot growth is promoted by enhanced shoot activities. In tomato plants, photosynthesis, stomatal conductance, and shoot weight were maximized by cooling the root-zone to 25°C at an air temperature of 40/23°C (day/night) (Nkansah and Ito, 1994, 1995a). Some similar studies have been reported (Kawasaki et al., 2013; Klock et al., 1997; Sasaki and Itagi, 1989). Around 20°C of root-zone heating increased leaf area, plant height, and relative growth rate (RGR) at low air temperature (16.2°C of daily mean temperature) (Kawasaki et al., 2014). In cucumber and tomato plants, the photosynthesis rate, stomatal conductance and shoot RGR increased with root-zone heating from 13°C to 19°C at an air temperature of 20/12°C (Wang et al., 2016). In the sweet pepper (Capsicum annuum L.), an increase in stomatal conductance and a decrease in leaf water potential were also observed, while the leaf area and dry weight of the whole plant increased, when the root-zone

![](image)

Fig. 1. Cascade of physiological reactions of root-zone temperature control under suboptimal air temperature conditions in tomato plants (Kawasaki et al., 2013, 2014). RZT: root zone temperature.
was cooled from 40°C to 20°C at an average daily maximum air temperature of 37.0°C (Dodd et al., 2000). In the lettuce (*Lactuca sativa* L.), root-zone cooling increased photosynthetic activities (He et al., 2001) and shoot dry weight (Ilahi et al., 2017).

These effects all ultimately lead to an increased yield. Chong and Ito (1982) reported that the total and marketable fruit yield of tomatoes were maximized when the root-zone temperature was kept at 20°C under a maximum air temperature exceeding 35°C; this had the added effect of reducing the occurrence of blossom-end-rot and abnormal fruits. However, some studies did not observe an increase in fruit yield, indicating that the effect of root-zone cooling on yield also depends on above-ground conditions (Gent and Ma, 1998; Papadopoulos and Tiessen, 1987). Root-zone heating at low air temperatures increased fruit yield and quality (Hurd and Graves, 1985; Jones et al., 1978; Kawasaki et al., 2014; Morgan and O’haire, 1978; Orchard, 1980). Specifically, Hurd and Graves (1985) and Jones et al. (1978) investigated energy consumption and benefits of root-zone heating, respectively, and indicated the commercial advantage of root-zone heating at low air temperatures. For the cucumber, root-zone cooling at high air temperature increased fruit number and weight (Moon et al., 2007b). For the sweet pepper, root-zone cooling in the warm season increased calcium content in fruits and reduced the incidence of blossom-end-rot (Benoit and Ceustermans, 2001). For the strawberry (*Fragaria × ananassa* Duch.), root-zone heating at low air temperature accelerated flower bud differentiation and flowering of axillary flower clusters, as well as increasing commercial fruit yield (Kim et al., 2009).

Furthermore, some reports showed that enhancement of plant growth and physiological activities by root-zone temperature control is mediated by plant growth regulators. Under optimum air temperature conditions, cytokinin (Ali et al., 1996; Kafkafi, 2001; Moon et al., 2007a), gibberellin (Ali et al., 1996; Moon et al., 2007a), and abscisic acid (Moon et al., 2007a) were affected in tomato and cucumber plants. Root-zone cooling at high air temperature caused auxin to mediate root growth in tomato plants (Kawasaki et al., 2013). However, auxin did not affect root growth with root-zone heating at low air temperature, indicating that the mechanism of root growth differs between root-zone heating and cooling (Kawasaki et al., 2014).

Root-zone temperature control techniques are generally used to keep roots at an optimum temperature and promote plant growth. On the other hand, it has been reported that excessive root-zone cooling increased fruit quality because of water stress on roots. Fujimura et al. (2012) chilled the root-zone of tomato plants from 20°C to 12°C in winter and reported that the dry weight and fruit sugar content increased, whereas the dry weight of vegetative organs decreased, especially in the leaves and roots.

**Local Temperature Control of Fruits**

Temperature has a large impact on fruit growth and ripening. Higher temperature promotes the fruit growth rate and shortens the number of days between flowering and harvesting in a suitable temperature range (Adams et al., 2001; Bertin, 2005). Fruit growth and ripening are affected by the temperature of the fruit itself, rather than the whole plant temperature (Kitano et al., 1998). Dorais et al. (2001) suggested a hypothesis that sink strength and dry matter distribution of fruit tend to increase with fruit temperature. Therefore, higher fruit production can be expected by heating fruits locally in the cold (winter) season.

Fanwoua et al. (2012) enclosed trusses of tomatoes into cuvettes with heating from approximately 22/18°C (day/night) to 27/23°C and reported that heating the fruit shortened the fruit growth period and reduced the final fruit size due to a reduction in the final pericarp cell volume. Gautier et al. (2005) tested fruit heating using 45°C water in flexible heating pipes circulating near growing cherry tomato fruits, and reported that the fresh weight, dry matter, and some secondary metabolites of the fruit were reduced. In these reports, the effectiveness of fruit heating of tomatoes was not shown. Fruit heating of tomatoes inhibits fruit production, contrary to expectations. On the other hand, the effectiveness of fruit heating was reported in the melon (*Cucumis melo* L.) and watermelon (*Citrullus lanatus* Matsum. et Nakai), in which sucrose accumulation was promoted in fruits (Kano, 2006; Kano et al., 2008, 2012; Matsumoto et al., 2012). The effects of fruit heating may therefore differ among crops.

In contrast to some reports on the effect of local heating of fruits, no information about local cooling on fruits was found. Because some effects of cooling fruits are thought to be prolonging the number of days between flowering and harvesting and increasing fruit size, a certain effectiveness is expected; however, dew drops on fruit that occur with cooling may contribute to the emergence of diseases and cuticle cracking.

**Local Temperature Control of Shoot-tips and Flowers**

Temperature control of shoot-tips had an impact on the differentiation of leaves and flower buds. Savvides et al. (2013) showed that the shoot-tip temperature deviated from air temperatures under moderate environments and measured a deviation range between −2.6°C and 3.8°C in tomatoes and between −4.1°C and 3.0°C in cucumbers, indicating that shoot-tip temperature in cucumbers was lower than that in tomatoes because of higher transpiration. Furthermore, these authors showed that the leaf differentiation rate of cucumbers derived only from the shoot-tip temperature, and not other temperatures (Savvides et al., 2016). Kawasaki et al. (2010) revealed that local heating of tomato shoot-tips from a
9.6°C to a 13.0°C surface temperature using electrical heaters in the winter season accelerated flower truss appearance (Table 2). Temperature of flower buds influences the fruit set ratio and directly impacts fruit yield. Kawasaki et al. (2010) heated flower trusses along with shoot-tips and showed that a higher flower temperature enhanced pollen viability, promoted fruit set and increased fruit yield.

Fine-tuning local temperature control of shoot-tips and flowers is difficult because shoot-tips and flowers in many vegetable plants grown in greenhouses are generally located near the plant canopy, and these positions are elevated with elongation growth. Instead of pinpoint control, therefore, vertical temperature gradients can offer practical local temperature control of shoot-tips and flowers, meaning that the upper parts containing shoot-tips and flowers are kept at an optimum temperature and the lower parts are not actively controlled. Kempkes et al. (2000) developed a temperature distribution model for greenhouse tomato production based on physical transport processes, including radiation, convection, and latent heat transfer, and simulated the effect of heating pipe positions. These authors also showed that the temperature and transpiration of the upper leaves, including shoot-tips and flowers, was increased when heating pipes were arranged close to the canopy, although air temperature increased only slightly, indicating that the use of heating pipes enables local heating, especially shoot-tip and flower heating. Kawasaki et al. (2011) tested the local heating of tomato shoot-tips and flowers using an air heater and plastic ducts hung near the plant canopy (Fig. 2), and demonstrated that the surface temperatures of shoot-tips and flowers were increased locally, whereas lower parts were maintained at low temperatures compared with a conventional duct arrangement laid on the ground (Fig. 3). In addition, the local heating reduced fuel consumption by 26% (Fig. 4), with a similar or higher yield (Table 3). Qian et al. (2015) also showed that growth and yield of tomato plants were not changed when the lower parts were maintained at temperatures lower than the optimum when the upper parts were maintained at optimum temperatures (25–15°C). This result indicates that the temperature of the lower parts of the plant has little effect on growth and yield, and is similar to that of

### Table 2. Effect of shoot-tip temperature on greenhouse tomato production at low air temperature (Kawasaki et al., 2010).

| Cultivar             | Temperature of shoot-tip and flower surface (°C) | Interval of truss appearance (day/truss) | Fruit set ratio (%) | Marketable fruit yield (kg/plant) | Marketable fruit number (/plant) | Individual fruit weight (g/fruit) |
|----------------------|-------------------------------------------------|------------------------------------------|---------------------|-----------------------------------|----------------------------------|----------------------------------|
| Reiyo                | 13.0                                            | 12.5                                     | 96.9                | 7.73                              | 45.6                             | 166.3                            |
|                      | 11.5                                            | 13.2                                     | 95.5                | 7.41                              | 43.0                             | 163.2                            |
|                      | 9.6                                             | 13.6                                     | 89.3                | 6.35                              | 37.3                             | 144.5                            |
| Momotaro Haruka      | 13.0                                            | 11.3                                     | 89.1                | 6.36                              | 40.4                             | 134.4                            |
|                      | 11.5                                            | 11.7                                     | 75.1                | 3.57                              | 23.8                             | 102.3                            |
|                      | 9.6                                             | 12.0                                     | 61.3                | 2.95                              | 18.8                             | 97.5                             |

ANOVA:
- Cultivar (C): **
- Temperature (T): **
- C × T: NS

* NS, * and ** indicate non-significant, significant difference at the 5% and 1% levels, respectively.
local heating of shoot-tips and flowers (Kawasaki et al., 2011).

Local cooling of shoot-tips and flowers under high air temperature is effective, as well as local heating under low air temperature. Kawasaki and Ahn (2015) reported that local cooling at night, using a heat pump that blows cold air on tomato shoot-tips and flowers, reduced their surface temperature approximately from 27°C to 25°C under a 30°C daily mean air temperature, leading to an increased fruit yield and marketable fruit ratio. Although local cooling has proven to be effective in increasing fruit production, its energy costs have not been reported. Therefore, further research on the economic benefits of local cooling is required.

For the strawberry, local temperature control has also been studied. Strawberries differ from the other fruit and vegetables, as they have shoot-tips (crowns) located near the ground surface, and their position does not move with growth. Crown temperature can be controlled easily by a system similar to that used for root-zone temperature control. Sato and Kitajima (2010) heated crowns using electrically heated wire to 21°C under an 8°C minimum daily temperature and observed that the differentiation of leaves and flower buds was accelerated, and that petiole elongation and flowering were promoted. Hidaka et al. (2017) cooled strawberry crowns to 20°C using a plastic tube filled with chilled water under high air temperature conditions (controlled day/night temperatures of 30/27°C) and showed acceleration of differentiation and flowering on first inflorescence, as well as an increased early marketable yield. Dan et al. (2015) demonstrated crown cooling in summer and heating in winter in a strawberry forcing culture and showed that marketable fruit yield increased by 9–15% when the crown temperature was

![Fig. 3. Thermal images of conventional heating (A) and of local heating around shoot-tips and flowers in tomato plants (B) (Kawasaki et al., 2011). Air heaters operated below a 13°C air temperature in both heating methods. Thermal sensors are located at the middles and tops of plants in conventional and local heating, respectively.](image)

![Fig. 4. The effect on fuel consumption of conventional heating and local heating around shoot-tips and flowers in tomato plants (Kawasaki et al., 2011).](image)

| Cultivar       | Heating     | Total  | Marketable |
|----------------|-------------|--------|------------|
|                |             | Yield (g/plant) | Fruit number | Fruit weight (g/fruit) | Yield (g/plant) | Fruit number | Fruit ratio (%) |
| Momotaro York | Conventional| 8093    | 56.4       | 143.4       | 5417       | 32.2          | 57.1         |
|                | Shoot-tip   | 7926    | 53.8       | 147.4       | 5655       | 32.9          | 61.1         |
| Bittorio       | Conventional| 9118    | 53.9       | 169.1       | 6184       | 30.0          | 55.7         |
|                | Shoot-tip   | 10570   | 56.7       | 186.3       | 7693       | 36.2          | 63.8         |
| ANOVA'         | Cultivar (C) | **      | NS         | **          | **         | NS            | NS           |
|                | Heating (H)  | NS      | NS         | *           | **         | **            | **           |
|                | C×H         | *       | *          | NS          | *          | NS            | NS           |

* NS, * and ** indicate non-significant, significant difference at the 5% and 1% levels, respectively.
kept around 20°C throughout the culture compared to the control condition.

Although the contribution of energy saving with local temperature control of shoot-tips and flowers has not yet been fully clarified, it will likely reduce energy consumption while resulting in the same yield compared to conventional methods where shoot-tip and flower temperatures are kept the same and the other parts are not actively temperature-controlled. Moreover, this technique can increase fruit yield with less energy consumption when the temperature is maintained nearer the optimal level than that of conventional techniques.

**Local Temperature Control of Other Parts**

Almost all studies on local temperature control of plant organs are described above; however, few reports are available on leaf and stem temperature control, as they are relatively insensitive to temperature changes compared to other organs (Table 1). On the other hand, basal stem heating ensured similar or greater effects on flower differentiation and fruit yield in the eggplant (*Solanum merongena* kouki) when its temperature was kept at 25°C and the set point of the heater was lowered to 10°C from 12°C (Moriyama and Oku, 2012; Moriyama et al., 2011). These authors also showed that fuel consumption was reduced by approximately 30% using basal stem heating with a 2°C lower heater setting. Furthermore, basal stem heating promoted the growth of lateral branches and differed from root-zone heating, which promoted primary stem and root growth (Moriyama et al., 2012). This difference could be due to a plant growth regulator; however, further studies are required to confirm this hypothesis.

**Conclusion and Perspectives**

Temperature management in greenhouses has primarily used uniform temperature conditions throughout the greenhouse. However, recent studies on the temperature reactions of each plant organ revealed that crops showed high productivity even when temperature conditions were not uniform. On the basis of these findings, local temperature control techniques have been developed to create accurate uniform temperature gradients. They can contribute to reducing energy expenditure and the associated environmental impact; therefore, greenhouse vegetable production using these techniques would be more beneficial than that using conventional temperature control techniques. On the other hand, there is little information on the exact cost reduction and the resulting lower environmental footprint. Furthermore, physiological mechanisms in plants benefiting from local temperature control are not well known, for example, gene expression and balance of plant growth regulators. More research on these areas is required in the future.

The combination of some local temperature control techniques could lead to higher productivity than that of a single technique; however, a combination technique would be more difficult to control and would increase the initial cost of the system. Therefore, more studies are necessary to develop the best technique for local temperature control that can be applied in greenhouse production.

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