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An Investigation of a Root Zone Heating System and Its Effects on the Morphology of Winter-Grown Green Peppers

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Abstract: The winter season in Nanjing is from December to February, with extremely low temperature and high humidity due to seasonal snowfall. During these extreme cold climatic conditions, plants have to survive severe heat stress conditions, even if they are being kept in greenhouses. The objective of this study was to investigate a heating system that can provide heat directly to the root zone instead of heating the entire greenhouse, which is a viable option to reduce energy consumption. Root zone heating could be an effective alternative for the sustainable development of plants during the winter. A novel type of root zone heating system was applied to evaluate the energy consumption during different greenhouse ambient temperature conditions, the effects of root zone heating systems on pepper plant morphology, and heat transfer rates to plant canopy in the greenhouse. The temperature treatments in root zone heating system were T-15, T-20, T-25, T-30, and a control treatment (TC) at 15 °C, 20 °C, 25 °C, and 30 °C, respectively, while TC received no heat. A simulation study was carried out to validate the root zone temperature. The results of the current investigation revealed that energy consumption has an inverse relationship to the ambient temperature of the greenhouse, while temperature gradients to the plant canopy observed from the lower to the upper part of the plant and the upper canopy experienced less temperature fluctuation as compared to the lower part of the plant. The results also showed that treatment T-20 had the maximum in terms of the leaf dry weight, stem diameter, and the number of leaves, while T-25 showed the maximum root dry weight and stem dry weight; T-30 and T-15 had minimum dry weights of plant segments among all treatments. Control treatment (TC) showed a minimum dry mass of plant. The root zone heating with optimal root zone temperature was found to be a viable and adaptable option as this leads to improved energy consumption patterns for the sustainable growth and development of plants in greenhouses during extremely low temperatures.

Keywords: energy consumption; sustainability; root zone; heating system; heat transfer; plants development; peppers; plant morphology

1. Introduction

Agriculture, as a production-oriented division, requires energy as an important input. The agricultural industry uses energy directly as electricity or fuel to drive machinery and equipment and for heating and cooling purposes. The concept of sustainable agriculture is geared towards increasing crop production and sustaining economic stability while reducing the exploitation of limited natural assets and harmful environmental effects. The Yangtze River Delta is one of China's most advanced, dynamic, densely inhabited industrial areas and is growing into a prominent world-class metropolitan area and performing a vital role in China's commercial and social growth [1]. It is famous for the intensive cultivation of crops [2] and faces extreme low temperature for one month with poor light and weather conditions. These severe conditions have a significant impact on horticultural productivity in non-heated greenhouses [3]. Greenhouse heating systems are needed for sustaining ideal ambient temperature conditions for the sustainable growth of plants and vegetables. Heating the root zone is a viable alternative instead of heating the whole greenhouse. The benefits of root zone heating have been attested to by many researchers. The quality and growth of crops are influenced by the soil temperatures in field as well as greenhouse conditions. Some other factors of the environment, i.e., temperature and light, also influence the growth and development of plants [1–4]. The growing medium acts as a substrate to stabilize and conserve the plant, while also performing the role of a basin conserving various nutrients, water, and heat [5]. Root zone temperature (RZT) is self-descriptive, giving the heat within the roots [6]. RZT influences the three core features of the growing medium, specifically physical, chemical, and biological, in disparate ways. Meanwhile, keeping the surroundings of the root zone consistent with the comfort zone encourages plant growth with efficient photosynthesis and reduced stress [5]. By controlling RZT suitably, the cultivation of tropical plants may be accomplished at an ambient air temperature of 7 °C with an RZT of 21 °C [7]. Cucumber, sweet pepper, and tomato plants were grown for 10 days at an RZT of 10 °C and 35 °C; the influence of root temperature was relatively small at low ambient air temperature [8]. The root zone temperature has a dynamic impact on the growth and development of various plants. Richards et al. [9] also accomplished numerous trials to investigate optimum, least, and extreme RZT for diversified plants. They noticed that root zone temperature had a significant impact on the dry weight and height of plants, although this impact on the growth of plants was partial.

The foremost benefits of a root zone heating system are preserving energy and attaining optimal growth. Jenkins et al. [10] studied the association between optimal plant growth and two kinds of heating structures in commercial-scale greenhouses, outer heating systems and plant top heating systems. They concluded that plant top heating systems consume almost 25% less energy compared to the outer heating system. The ambient temperature in a greenhouse might be decreased by 10 °C by sustaining optimal RZT [11]. The reduction in ambient temperature minimizes the temperature variation between the greenhouse internal and external walls, which significantly reduces the consumption energy. Likewise, this helps to attain optimal root temperatures and is cost-effective compared to directly heating the root zone because of the lower demand for fuel [12]. Conversely, it has been observed that bench-top heating systems cannot meet the heat requirements of greenhouses; as a result, the temperature is unequally distributed in the canopy [11]. In the case of ambient humid conditions and uncontrolled RZT, highly concentrated light and extreme temperatures hamper the growth of vegetables [13,14]. The morphology of the root depends on its growth rate and maturing. Transformations in the morphology of the root are apparent when there are high or low root temperatures. Optimal root temperature treatment higher than 30 °C, depending on the type and condition of the plant, results in faster cell partition and maturing; with brown roots, filamentous, less diameter, non-succulent, more superb branches and lateral roots closer to the tips of growth and fewer curls on the roots as compared to plant roots cultivated at root temperatures lower than 30 °C [15–17]. Nielsen [18] found efficient stability in water, carbohydrates, and nutrients between the root and shoot. Reduced growth of roots and maturing at extreme root zone temperatures lead to reduced growth of shoots [16,17].

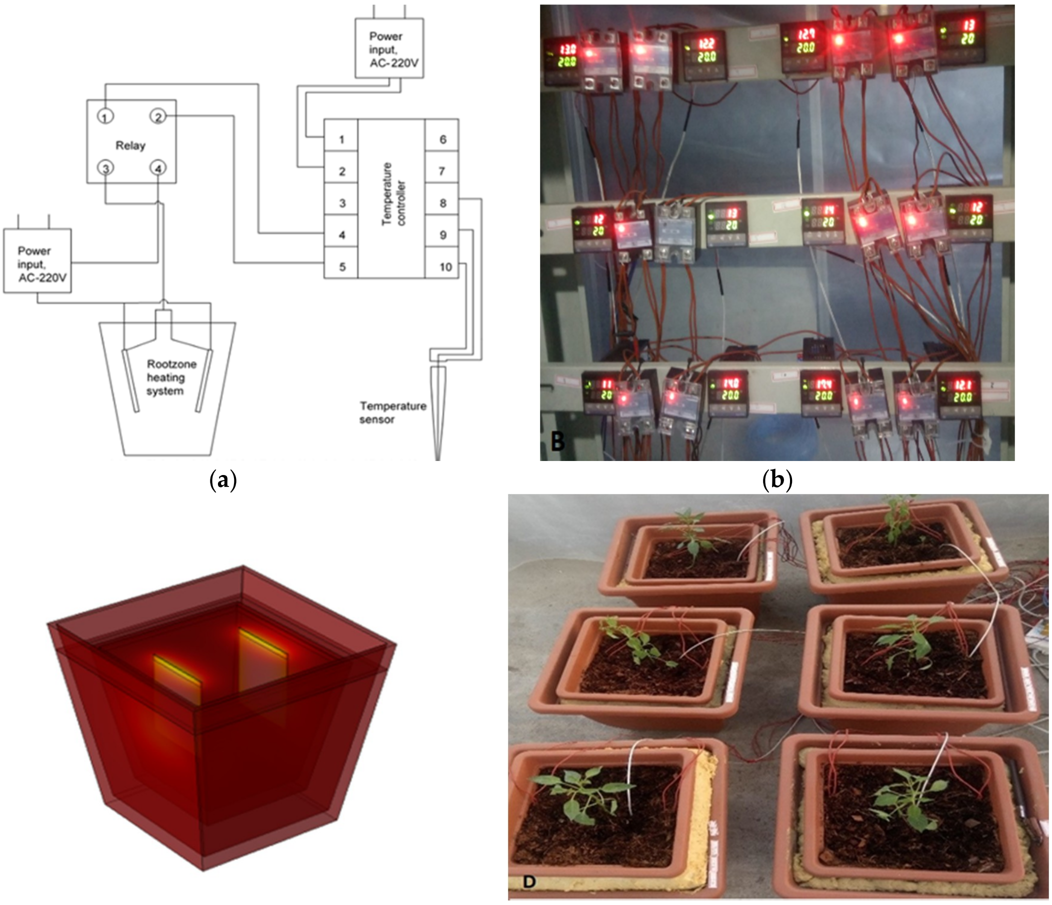
Pepper development at different root-zone temperatures has not been assessed before in hot aerial environments. Though they had shoot temperatures of 23 °C in the day and 19 °C at night, pepper plants experienced improved development with a rise in the temperature of the root zone to 30 °C; however, an adverse response may occur in leaf areas and in terms of dry weight due to a rise in RZ temperature to 36 °C [19,20].

In Nanjing, winter lasts from December to February and is marked by cold temperatures, high humidity, and occasional snow. January is the coldest month, with a low temperature dropping to −7 °C. In December and February, the average low temperature is 0 °C. During these extreme cold conditions, plants experience temperature stress even in greenhouses. To mitigate this problem, there is a need for new investigations into adaptable heating systems; root zone heating is also a good option to support plant life during these cold months and minimize energy consumption. A novel type of root zone heating system was used to verify its effects on the morphology of pepper plants in greenhouses with the objective of controlling greenhouse RZT during extreme winter conditions. The main purpose is to verify the effects of root zone heating on the development of winter-grown green pepper plants and extract valuable information that could be beneficial to farmers in cold regions of China. Moreover, the objective of this study is to optimize the root zone temperature, which could significantly improve pepper growth during extremely low temperatures in winter.

2. Materials and Methods

2.1. Experimental Setup

Experiments were conducted at the Engineering College, Nanjing Agricultural University, in a greenhouse. In this study, five different temperature conditions with three replicates were tested to check the morphological effects of root zone heating on winter-grown pepper plants. These treatments were T-15, T-20, T-25, T-30, and control treatment (TC). Treatment T-15 used a 15 °C root zone temperature, T-20 was 20 °C RZT, T-25 was 25 °C RZT, T-30 was 30 °C RZT, and TC was used as the control treatment without root zone heating. For this study, 15 insulated growing pots were used for root zone heating and investigating the heat transfer rates to different canopy parts of the pepper plant during different ambient temperature conditions and the morphological effects, as shown in Figure 1c,d. To observe and regulate the current root zone heating system, a control system was also used, as shown in Figure 1, Images A and B. The sensor [21,22] probe was a PT100 model WZP-001PC with a measuring range of −200–500 °C, made of stainless steel, with an accuracy of ±0.5 (Nanpac, Chongqing, China). It was fixed near the root zone inside the soil at a depth of 13 cm, as shown in Figure 1a. The data collection on hourly root zone temperature was conducted in the middle point of the growing medium, which corresponded with the root zone. Thermocouple model REX-C100FK02 (RKC Instrument, Tokyo, Japan), measuring a temperature range of 0 to 400 °C with an accuracy of ±0.5 and working voltage of 220 V, was used to control and measure the soil temperature differences. Infrared Thermometer model AS852B with measuring temperature range −50–750 °C, measuring accuracy ±2% and powered by a 9 V battery (Smart Sensor, Dongguan, China), was used to collect hourly data on the plant canopy temperature. This experiment was conducted during extreme low ambient temperatures (lowest ambient temperature −1 °C). The temperature set points on the temperature control system for the root zone were according to the treatment plan. Whenever the RZT crossed the set temperature of the controller, it cuts off the power to the heating source. The heat transfer to root zone, to stem of plants, and finally to leaves of a plant was investigated and carried out over three days. The treatments for the heating period continued for 32 days. Greenhouse ambient temperature readings were also collected hourly. Natural ventilation was created when required by rolling up the plastic cover on the two sides of the greenhouse.



(c) (d)

Figure 1. Root zone heating system: (**a**) Heating system wire diagram; (**b**) Thermocouples for heating control; (**c**) Heating pot with a heating source; (**d**) Experimental heating system.

2.2. Plant Material and Growth Conditions

Experiments were conducted from 25 December 2017 to 5 February 2018 using pepper cuttings with the same height, stem diameter, and the number of leaves. They were transplanted into the root zone with a base area of 289 cm^2 (17 × 17cm) and top area 676 cm^2 (26 × 26 cm) while the height of pot was 26 cm. These cuttings were chosen from a local nursery. Micronutrients were provided to all plants of all treatments, and necessary irrigation was applied. All initial data on the number of leaves and plant height were recorded. The growing medium used for the current investigation was coconut peat (Galuku Pvt. Ltd., Colombo, Srilanka). After transplanting, all plants were left for one week to achieve homogeneity in the root zone.

Root zone heating was provided to all plants according to the treatment plan, and this heating process lasted for 32 days. After five weeks all plants were removed from heating pots for further investigation. Roots and leaves with branches were separated from plants. The height of the stem, root height, number of leaves, and fresh weight were recorded. All the separated segments were oven-dried for 72 h at 70 °C to obtain the dry mass.

2.3. Energy Consumption

During this experimental investigation, mean daily energy consumption was also calculated using Equation (1) for more than four weeks. The purpose was to calculate the energy consumption of all heated treatments separately during different greenhouse ambient temperature conditions. Specific energy consumption for root dry mass was calculated using Equation (2).

$$\text{Mean Daily Energy Consumption (kWh)} = \text{(Power of Heating Source)}\cdot\text{(Operational Hours)} \quad (1)$$

$$\text{Specific Energy Consumption (kWh/g)} = \text{Total Energy Consumption/Dry Mass} \quad (2)$$

2.4. Simulation

A simulation study was also performed to check the heat flux throughout the pot of growing media. The COMSOL Multiphysics 5.1a Package software (Comsol, Beijing, China), which has different kinds of heat transfer models, including heat transfer in porous media, was used in the current simulation study and the Porous Media Module was used for heat transfer during this investigation [23–26]. The interval analysis time was one hour. The heating source remained switched on for six hours and switched off for the next six hours. Heat exchange between the environment and the system was also permitted. The main equation for the present study is derived from the heat transfer in the porous media module:

$$\left(\rho C_\rho\right)_{eff}\frac{\partial T}{\partial t} + \rho C_\rho u.\nabla T + \nabla.q = Q + Q_{vd} \quad (3)$$

In the above equation ρ = Soil density (kg/m^3), Cp = specific heat capacity (J/(kg·K)), T = absolute temperature (K), u = field velocity, q = conductive heat flux (W/m^2), α = thermal expansion coefficient (1/K), Q = additional heat sources (W/m^3), and Qvd = Viscous Dissipation.

2.5. Statistical Analysis

For this study complete randomized design was considered as the experimental design with three replications. For data processing and generation of graphs, statistical analysis Excel 2010 and Statistix 8.1 were used. Analysis of difference (ANOVA) was applied to statistically assess the significance across all behaviors, and the Tukey HSD (honestly significant difference) multiple comparison tests with an alpha value of 0.05 was used, which is one of several tests that can be used to determine which among a set of means differ from the rest.

3. Results and Discussion

Figure 2 illustrates the hourly heat flux throughout the pot in a growing medium. It can be observed in image A that as the heating process initiated the initial average temperature was 2 °C. The simulated results show ab increased root zone temperature in image A of Figure 2 after one hour. This root zone temperature incline continued up to image I in Figure 2, while the heat flux throughout the pot showed a continuous expansion, which can be observed during the last hour, as shown in image M of Figure 2. Figure 3 illustrates the correlation of the experimental mean root zone temperature and simulated root zone temperature. The increasing trend of root zone temperature in both methods is shown in Figure 3 from 12 p.m. to 6 p.m., while after this increase the experimental root zone temperature showed a slight decline from 6 p.m. to 12:00 a.m. The declining trend of simulated root zone temperature started from 8 p.m. to 12 a.m., and the maximum simulated root zone temperature was found at 8 p.m., while the maximum experimental root zone temperature was at 6 p.m.

The temperature analysis of the root zone of different heated treatments, unheated control treatment, and the ambient temperature is presented in Figure 4 and Table 1. The data were collected from 12:00 p.m. until midnight (0:00) and, during this time period, the ambient temperature showed a continuously decreasing trend with extreme values of 3.6 °C and 0.3 °C. Each plant was supplied with an identical power source to increase the root zone temperature to 15 °C for T-15, 20 °C for T-20, 25 °C for T-25, and 30 °C for T-30, respectively. Figure 4 shows that the switch-off time was different depending on the treatment plan, but every plant root zone showed a similar trend in temperature. Treatments T15, T20, T25, and T30 attained the required temperature state after 3, 4, and 5 h, respectively. It was clear that treatments T20 and T25 had the same temperature at 9 p.m. and showed the same trend thereafter, while the root zone temperature of the control treatment showed a decreasing trend similar to that of ambient temperature.

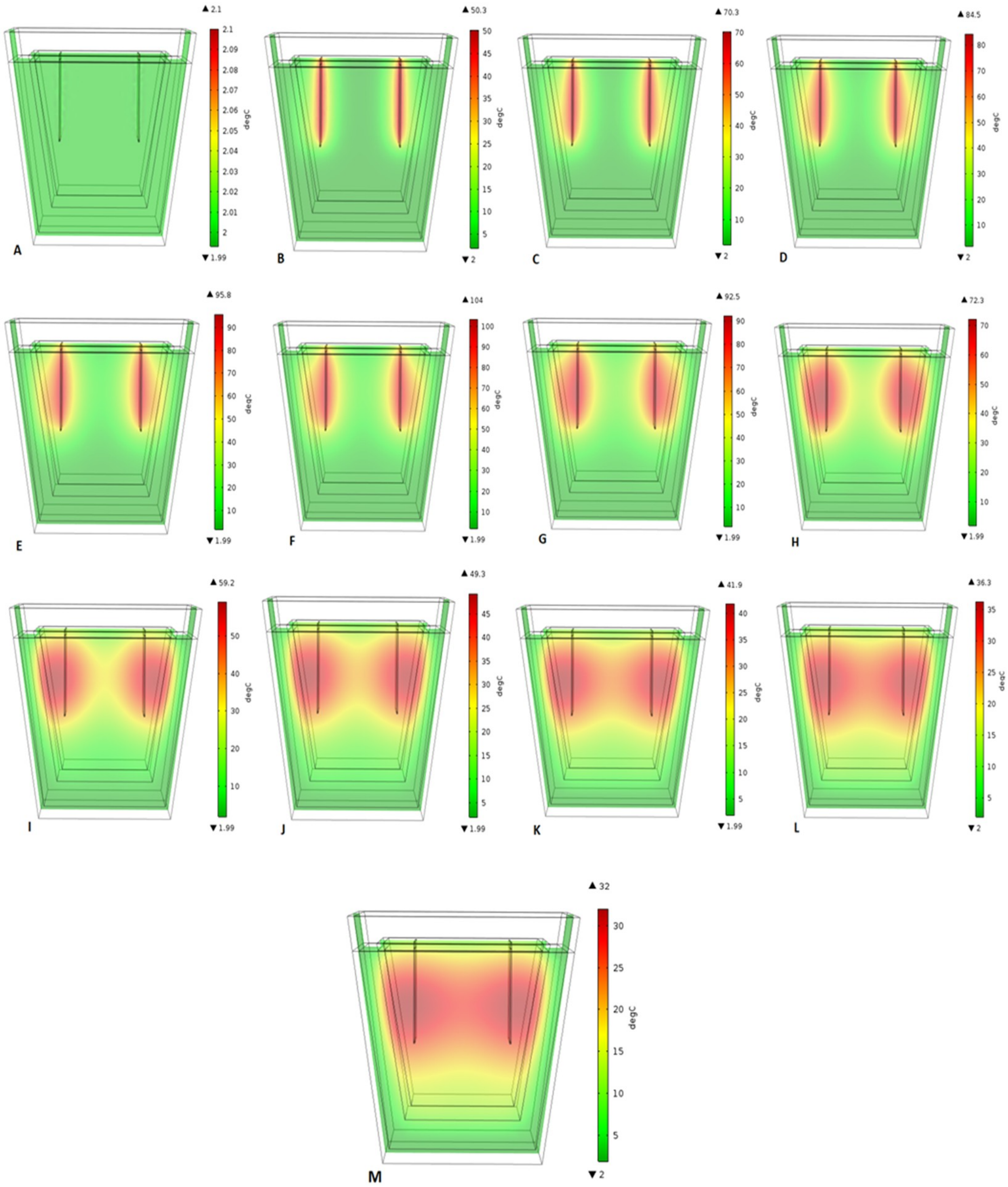


Figure 2. Hourly simulated heat flux in root zone heating pot over 12 hours of heating. Note: (A) = 1st hour, (B) = 2nd hour, (C) = 3rd hour, (D) = 4th hour, (E) = 5th hour, (F) = 6th hour, (G) = 7th hour, (H) = 8th hour, (I) = 9th hour, (J) = 10th hour, (K) = 11th hour, (L) = 12th hour, (M) = 13th hour.

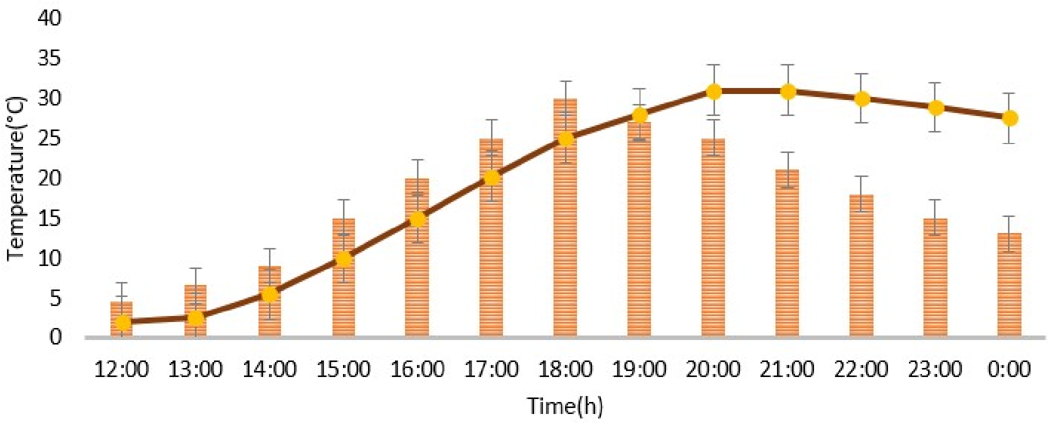


Figure 3. Hourly simulated and mean root zone temperature comparison.

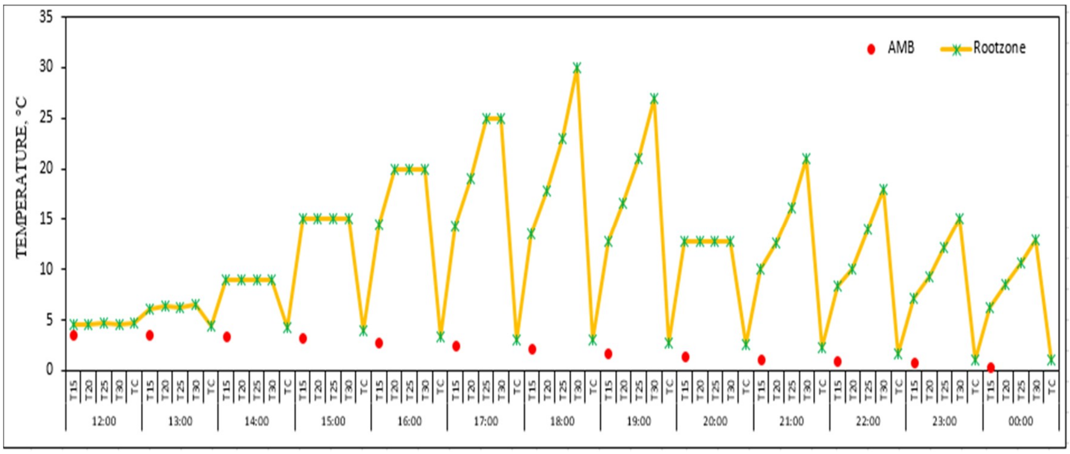


Figure 4. Temperature analysis in the plant root zone.

Table 1. Hourly root zone temperature variation analysis. The values presented in the table are the mean ±SD (standard deviation).

Time	Root Zone Temperature (°C)				
	Non-Heated	Heated			
	TC	T-15	T-20	T-25	T-30
12:00	4.7 ± 0.11	4.6 ± 0.17	4.5 ± 0.20	4.7 ± 0.11	4.6 ± 0.22
13:00	4.4 ± 0.11	6.1 ± 0.12	6.4 ± 0.17	6.2 ± 0.20	6.5 ± 0.10
14:00	4.2 ± 0.20	9.0 ± 0.10	9.0 ± 0.26	9.1 ± 0.27	9.3 ± 0.26
15:00	3.9 ± 0.14	15.0 ± 0.30	15.0 ± 0.20	15.0 ± 0.3	15.0 ± 0.31
16:00	3.3 ± 0.30	14.5 ± 0.26	19.9 ± 0.60	20.1 ± 0.26	19.9 ± 0.35
17:00	3.1 ± 0.10	14.3 ± 0.17	19.0 ± 0.27	24.9 ± 0.35	25.0 ± 0.43
18:00	3.0 ± 0.11	13.6 ± 0.20	17.8 ± 0.20	23.0 ± 0.26	30.0 ± 0.39
19:00	2.8 ± 0.09	12.7 ± 0.15	16.6 ± 0.11	21.0 ± 0.54	27.1 ± 0.43
20:00	2.6 ± 0.12	11.4 ± 0.40	14.0 ± 0.44	18.1 ± 0.34	25.0 ± 0.36
21:00	2.3 ± 0.11	10.0 ± 0.43	12.6 ± 0.11	16.1 ± 0.12	21.3 ± 0.47
22:00	1.5 ± 0.15	8.4 ± 0.12	10.0 ± 0.10	14.0 ± 0.43	18.1 ± 0.12
23:00	1.1 ± 0.11	7.1 ± 0.17	9.2 ± 0.20	12.1 ± 0.14	15.0 ± 0.32
00:00	1.0 ± 0.12	6.2 ± 0.30	8.5 ± 0.35	10.3 ± 0.20	12.9 ± 0.13

The analysis of plant canopy temperature under the result of root zone heating at different temperatures is presented in Figure 5. The root zone heated with different temperature treatments had a different temperature at different levels as the whole plant was divided into three parts: the lower canopy, middle canopy, and top canopy. The lower canopy got more heat as compared to the middle and top. The temperature trend (incline versus decline) is similar in all three parts, as can be observed from Figure 5. The maximum temperature values were found in the lower canopy of T-30, followed by T-25, while the minimum values were found in control treatment TC with no heating system. The results of plant canopy heat distribution also illustrate that, as the ambient temperature showed a continuous drop, the canopy temperature of control treatment also showed a continuous decline. According to the root zone temperature treatment plan, all treatment temperature values of all parts of the plant canopy were found to be below the set temperature. The maximum temperature of the lower canopy was 16 °C, found at 6 p.m. in T-30, while the minimum temperature of the lower canopy was 1 °C, found at 12 a.m. in TC. The maximum temperature of the middle canopy was 10.72 °C, established at 6 p.m. in T-30, and the minimum temperature of the middle canopy was 1 °C, found at 12 a.m. in TC. The maximum temperature of the top canopy was 10.02 °C, observed at 6 p.m. in T-30, and the minimum temperature of the top canopy was 1.16 °C, found at 12 a.m. in TC.

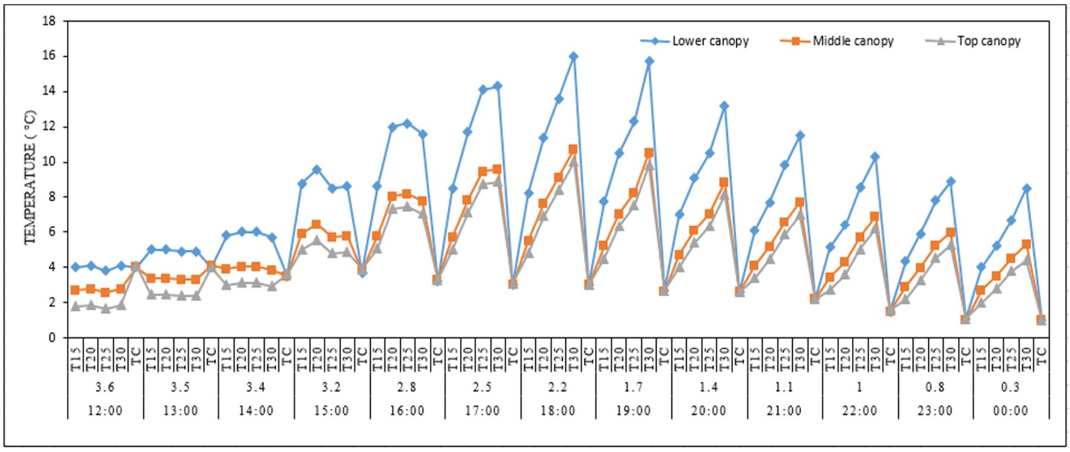


Figure 5. Temperature analysis of plant lower, middle, and top canopy.

Figure 6 illustrates the total energy consumption over a month. All treatments had different values of energy consumption depending on the ambient temperature. The results showed that if the ambient temperature was higher, the energy consumption was lower, while a decrease in ambient temperature led to an increase in energy consumption. The ambient temperature trend results illustrate that from 3 January to 8 January there was a minor fluctuation, but a sharp incline in the ambient temperature could be observed from 9 January until 13 January. Similarly, the energy consumption during this period also showed a similar trend to the ambient temperature. In the period from 14 January to 22 January the ambient temperature dropped from 17.3 °C to 3.7°C, when there was the lowest energy consumption because of the higher ambient temperature; during this period T-15 and T-20 had no energy consumption because the heating was not required. The lowest energy consumption was also found during this period.

Figure 7 shows the effects of the root zone heating system on plant growth. The analysis was performed for green pepper plants treated at five different RZT (15 °C, 20 °C, 25 °C, 30 °C and at the ambient RZT TC) for five weeks. The root fresh weight (RFW) was minimal in plants in the TC treatment, and the maximum RFW was found in T-25 group plants. Treatment T-20 had lower RFW compared to T-25, but higher RFW compared to T-15, T-30, and Tc. The maximum root dry weight (RDW) was obtained in T-25, and the minimum RDW was found in TC. Treatment T-20 had a RDW of 0.47 g, which was less than T-25, while T-20 RDW was higher compared to T-15, T-30, and TC. Treatment T-25 had a higher root water content (RWC) in the as compared to T-15, T-30, and TC. The optimal temperature plays a vital role in water and nutrient uptake and shows good root development. The dry matter of the plant is the key parameter of morphological development. The different investigators verified in their studies that fertilizer uptake is almost entirely determined by plant dry mass creation [27]. The root zone temperature effect on root dry mass could be clarified by subsequent studies that propose that a continuous uptake of nutrients is sustained over a wide range of temperature and exterior nutrient concentrations [28]. The roots are perhaps the most significant part of the plant because the root mass of the plant is directly proportional to the size and production of the plant. To boost plant growth energy is provided to raise the metabolic rate, to improve the uptake of nutrients the provision of natural hormones and vitamins that may be missing in hydroponic nutrient formulations is facilitated [29]. Table 2 illustrates that specific energy consumption for root dry mass was minimum in T-20 while the maximum specific energy consumption was found in T-30. Higher root zone temperature had adverse effects on root development and root dry mass production.

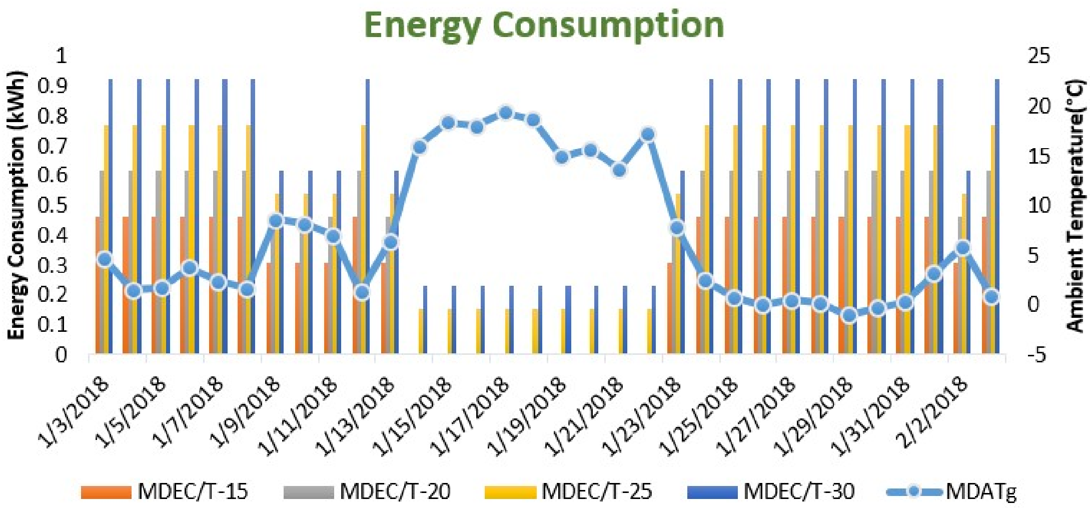


Figure 6. Total energy consumption of different treatments with different ambient temperature conditions.

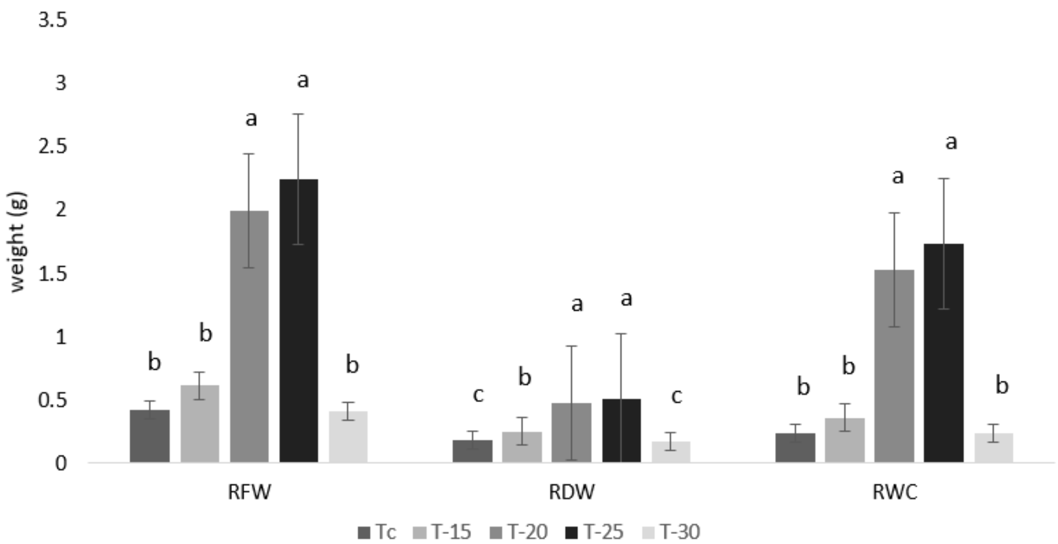


Figure 7. Root fresh and dry mass graph. RFW = Root fresh weight (g), RDW = Root dry weight (g) and RWC = Root water content (g). Tukey honestly significant difference (HSD) multiple comparison tests with alpha value 0.05 were performed. Standard Error for Comparison (SE) for RFW = ±0.16, RDW = 0.02 and RWC = ±0.15.

Table 2. Specific energy consumption for root dry mass.

Specific Energy Consumption (Roots)			
Treatment	**Dry Mass (g)**	**Total Energy Consumption (kWh)**	**Specific Energy Consumption (kWh/g)**
T-15	0.2513	9.702	38.61
T-20	0.4713	13.244	28.1
T-25	0.5077	17.71	34.88
T-30	0.1717	21.483	125.11

The root zone heating had an influence on the pepper leaf fresh weight (LFW), leaf dry weight (LDW), and leaf water content (LWC), as shown in Figure 8. Treatment T-20 showed the maximum LFW, while the control treatment had the lowest LFW. Treatment T-25 was significantly different and had a higher LDW as compared to T-15, T-30, and the control treatment, while it had a lower LDW compared to T-20. Similarly, T-20 was significantly different and had a higher LDW as compared to T-15, T-25, T-30, and TC. The minimum LDW was found in TC. T-25 had a LDW of 0.7463 g, which is higher than in T-15, T-30, and TC. High leaf dry matter production was found for T-20 and T-25, which is close to the findings of Fujishige and Sugiyama [30]. They cultivated cucumber, sweet pepper, and tomato plants at RZT at 10 °C and 35 °C for 10 days. Furthermore, they investigated the effect of RZT, which was relatively less significant at low ambient air temperature as compared to the observations of Jones et al. [31], Sandwell [32], and Gosselin and Trudel [33].

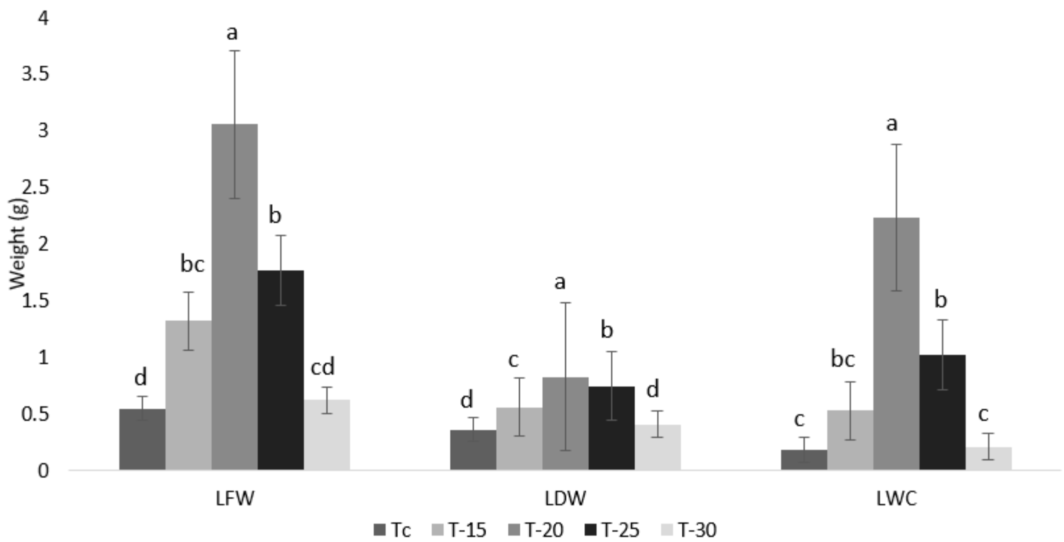


Figure 8. Leaf fresh and dry mass graph. LFW = Leaf fresh weight (g), LDW = Leaf dry weight (g), and LWC = Leaf water content (g). Tukey HSD multiple comparison tests with alpha value 0.05 were performed. Standard Error for Comparison (SE) for LFW = ±0.22, LDW = 0.02 and LWC = ±0.23.

Figure 9 shows that RZH also affected stem fresh weight (SFW), stem dry weight (SDW), and stem water content (SWC). It was observed that the fresh weight of stem was highest in T-25, at 2.422 g, and the minimum stem fresh weight was in TC, 0.554 g. Treatment T-30 had higher stem fresh weight compared to T-15, T-20, and TC. T-20 had higher stem fresh weight as compared to T-15 and TC. Similarly, RZH showed variations in stem dry weights in all treatments. The maximum stem dry weight was found in T-25, 1.124 g, and the minimum stem dry weight was observed in TC, 0.359 g. The dry weight of the stem in T-15 was calculated to be 0.383 g, and in T-20 the stem dry weight was a little higher, 0.771 g. T-30 had a stem dry weight 1.037 g lower than T-25's.

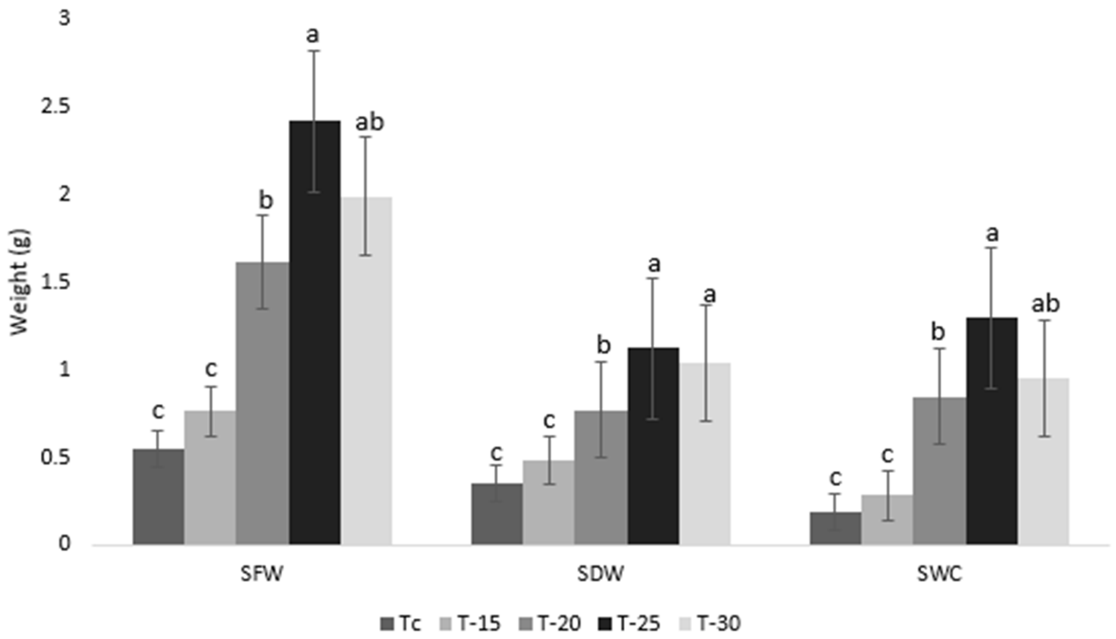


Figure 9. Stem fresh and dry mass graph. SFW = Stem fresh weight (g), SDW = Stem dry weight (g), and SWC = Stem water content (g). Tukey HSD multiple comparison tests with alpha value 0.05 were performed. Standard Error for Comparison (SE) for SFW = ±0.16, SDW = 0.07 and SWC = ±0.12.

A relationship between the diameter of the plant stem and RZT (15 °C, 20 °C, 25 °C, 30 °C, and at ambient RZT TC) was also observed under different temperature treatments. An increase in stem diameter was measured after four weeks of treatment, as shown in Figure 10. The figure shows both the initial and the final diameter of plant stems under variable temperature conditions, along with the control treatment. The maximum initial diameter was measured in the T-30 treatment, followed by the T-15 treatment with 1.71 mm, while the lowest stem initial diameter was found in treatment T-20. On the other hand, after four weeks the maximum final stem diameter, found in the T-20 treatment, was 4.48 mm, with a 2.92 mm net increase in diameter, which is 65% higher than the initial plant stem diameter. T-30 had the lowest increment in stem diameter 1.02 mm (36%) among all the treatments, while the least net increased diametric growth, 0.82 (33%), was found in the control treatment.

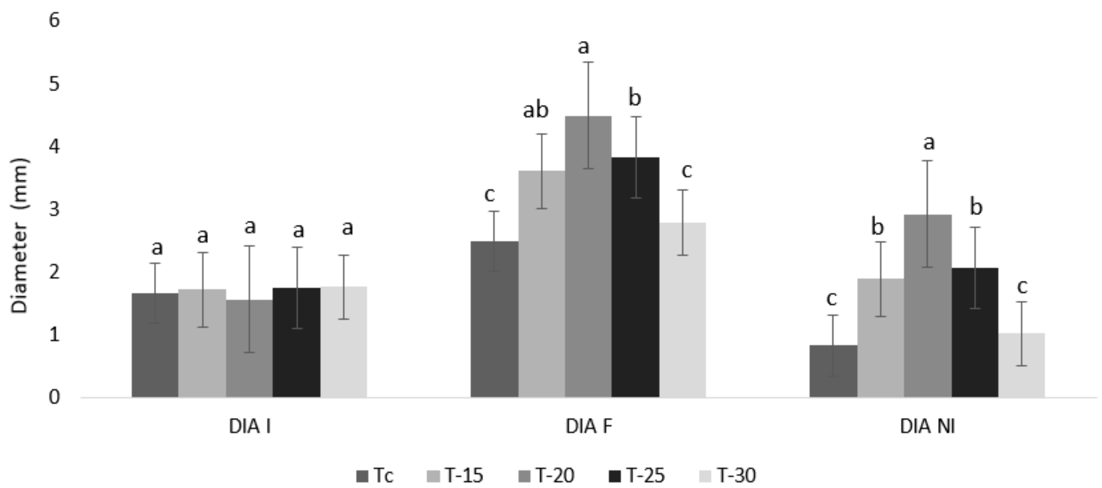


Figure 10. Stem diameter (mm) growth according to different treatments. Tukey HSD multiple comparison tests with alpha value 0.05 were performed. Standard Error for Comparison (SE) for DIA I (diameter initial)= ±0, 06, DIA F(diameter final) = ±0.22 and DIA NI(diameter net increase) = ±0.25.

The analysis conducted for an average number of leaves under different temperature conditions for four weeks is shown in Figure 11. The figure depicts the average number of leaves before and at the final stage of the experiment. The average number of leaves on every plant at the initial and final stage, along with the net increase in leaves under different temperature conditions, is presented in this figure. At the initial stage of the experiment, it was found that the plants had the same average number of leaves in treatments T-20, T-25, and T-30, while the plant in control treatment had the lowest average number of leaves. The final number of leaves was highest in T-20, with a net increase of 64%, followed by T-25 (a 54% net increase in leaves). The plants treated at 30 °C (T-30) showed the lowest growth in leaves (33%) among the treatment groups, while the control group produced the fewest leaves on average (30% less). In some plants, a lower root zone temperature resulted in reduced or inhibited photosynthesis [34]. A high root zone temperature inhibited the growth and fruit yield of sweet peppers compared to other treatments [35,36].

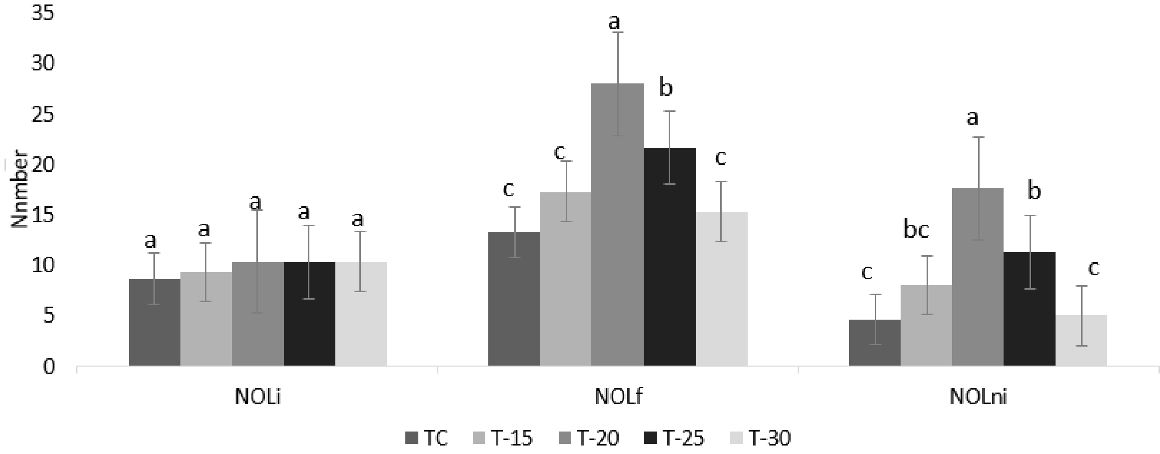


Figure 11. Initial and final number of leaves according to different treatments. Tukey HSD multiple comparison tests with alpha value 0.05 were performed. Standard Error for Comparison (SE) for number of leaves initial (NOLi) = ±0.86, number of leaves final (NOLf) = ±1.28 and number of leaves net increase (NOLni) = ±1.88.

Figure 12 shows the comparative analysis carried out to evaluate the effects of root zone heating systems on root length (RL) and shoot length (SL) of plants under variable temperature conditions. The figure shows the growth in terms of root length and shoot length of plants. The plants in the T-25 and T-20 treatments showed significant growth both in root length and shoot length, as shown in the figure. The growth found in the T-15 and T-30 treatments was non-significant. The plants under control treatment showed the lowest increase in root length and shoot length. The leafy vegetables cultivated in a greenhouse were treated at a higher temperature (25 °C) and lower temperature (15 °C); the RZT showed a smaller plant size as compared to plants treated at a moderate temperature (20 °C) [37]. The increase in plant height because of raised RZT was a result of the long internodes in potato plants [38]. Moreover, nutrient uptake and root growth were inhibited due to higher and lower RZT [39,40]. Furthermore, higher and lower RZT affect growth, gas exchange, photosynthesis, and survival following transplanting [41]. Root zone temperature regulation is important for vegetable health and production [42].

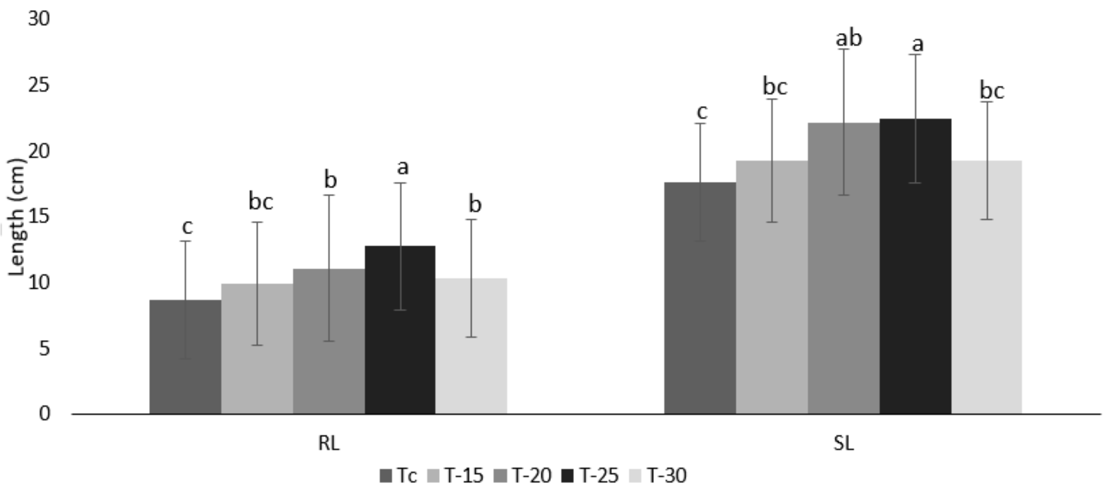


Figure 12. Root and shoot length (cm) according to different treatments. Tukey HSD multiple comparison tests with alpha value 0.05 were performed. Standard Error for Comparison (SE) for root length (RL) = ±0.39 and shoot length (SL) = ±0.89.

4. Conclusions

The root zone heating system was used to investigate the simulated and experimental root zone temperature, energy consumption, and heat transfer rates to the plants' lower, middle, and top canopy during winter. The developmental response of plants by using different root zone temperature treatments was also analyzed. The results revealed that if the ambient temperature increases the energy consumption will be decreased while specific energy consumption for root dry mass production was found feasible in T-20. The maximum root dry mass production with minimum energy consumption was found in T-20. Heat transfer analysis for plant canopy indicated that the temperature of the lower canopy was higher as compared to the middle and upper canopy of the plant as heat transfer was from the root zone to the top canopy of the plant. In the current system, the heat transfer to the plant canopy proved more viable as the heating source was within the growing medium, while other root zone heating systems like a benchtop root zone heating system have lower heat transfer rates to the plant canopy as the heating source is not fixed within growing medium. The current investigation revealed that all the heated plants showed viable plant development as compared to non-heated plants.

The results for the dry mass of different segments of plants, such as roots, stem, and leaves, also showed differences among treatments. T-20 had the highest leaf dry weight, stem diameter, and number of leaves, while T-25 had the highest root dry weight and stem dry weight. T-30 and T-15 had the minimum dry weight of plant segments in all heated treatments. TC has the minimum dry mass production as compared to all root zone heated treatments. The T-20 and T-25 root zone temperatures were found to be optimal, but the most significant root zone temperature should continue to be a focus of future research related to pepper plants. It can be concluded that root zone heating is a viable option to reduce energy consumption and the maintainable development of pepper plants during extremely low temperatures in the winter. It could be of future interest to study other crop responses to root zone heating and to optimize specific energy consumption.

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