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# Effect of Cooling Root-Zone Temperature on Growth, Yield and Nutrient Uptake in Cucumber Grown in Hydroponic System During Summer Season in Cooled Greenhouse

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**Abstract**

Optimum cool root zone temperature positively influences the production of greenhouse vegetables grown during summer/high temperature period under hydroponics system. Hence, the effect of root-zone temperature was investigated on the growth, yield and nutrient uptake of cucumber (*Cucumis sativus* L.) plants grown in pots filled with perlite medium under recirculating hydroponic system in greenhouse during summer period (June-August) in two consecutive years 2016/2017 and 2017/2018 using three cooling treatments-T1 (22 ºC), T2 (25 ºC) and T3 (28 ºC) and non-cooled treatment T4 (33 ºC) as control in Randomized Complete Design (RCD). All the treatments received the same nutrient concentrations. Significant ($p < 0.05$) differences were observed for all the characters viz. plant height, leaf number/m$^2$, chlorophyll content, leaf area (cm$^2$), fruit number /m$^2$, yield (t/gh), fresh (g) and dry matter weight (g) of shoot and root at all cooled root-zone temperatures as compared to control in both the years. Plants at cooled root-zone temperature (RZT) of 22 ºC gave high number of fruits/m$^2$ to the extent of 180 in 2016/2017 and 220 in 2017/2018 followed by that at 25 ºC (167, 221) and 28 ºC (178, 143) as compared to those in control (33 ºC) (101,133) in both the years. Similarly, highest fruit yields were found at cooled RZT of 22 ºC (5.0 t/gh) and 28 ºC (4.7 t/gh) in the first year and 22 ºC (6.1 t/gh) and 25 ºC (6.0 t/gh) in the second year. The plants at cooled RZT responded positively and significantly ($p < 0.05$) in the uptake of all nutrient elements in shoots and roots in comparison with those at non-cooled RZT in both years.

**Keywords:** root-zone, temperature, growth, yield, hydroponics, cucumber

## 1. Introduction

While the air temperature is one of the most important environmental elements for the altering secondary metabolism in the plants for production (Kaplan et al., 2004; Zobayed et al., 2005; Ramakrishna & Ravishankar, 2011), the temperature at the root-zone also influences the growth and chemical composition of many plants (Adebooye et al., 2010; Malik et al., 2013; Yan et al., 2013; Sakamoto & Suzuki, 2015a, 2015b). One of the characteristics of hydroponic cultivation is its ability to control the temperature of the nutrient solution around the root system using heaters or cooling spirals, to increase or decrease the temperature, respectively. During the midday period, in the hot summers, the root-zone temperature of hydroponic systems often exceeds 30 ºC. The root-zone temperature can often reach 35 ºC when the air temperature is 38 ºC. This was strongly found to suppress the plant growth process and reduce uptake of water and nutrients (Mozafar et al., 1993; Marschner et al., 1996; Stoltzfus et al., 1998). Several studies on different species have shown that plant growth is greatly influenced by root zone temperature (Lyr & Garbe, 1995; Lahti et al., 2005; Solfjeld & Johnsen, 2006; Dıaz-Perez et al., 2007; Nxawe et al., 2009). Although, plant growth is controlled by various factors, root zone temperature and nutrient supply indicate that RZT is crucially an important factor in plant nutrient uptake. In view of the above, the study was designed to investigate the effect of root-zone temperature on the growth and yield of cucumber (*Cucumis sativus* L.).

## 2. Materials and Methods

Seeds of cucumber variety namely; Reema F1 (Trust Seeds ) were sown in 72 hole trays on 11/5/2016 and 9/5/2017 and transplanted after 10 days in polyfoam pots filled with perlite medium under recirculating hydroponic system in the greenhouse of 270 $m^2$ (9 m × 30 m) during summer (June-August) in two consecutive years 2016/2017 and 2017/2018 at the research site of the Directorate General of Agriculture and Livestock Research, Ministry of Agriculture & Fisheries, located at Rumais, Wilayat Barka, South Batinah Governorate of Oman. Three cooling treatments were applied; T1 (22 ºC), T2 (25 ºC) and T3 (28 ºC) through cooling nutrient solution along with non-cooled treatment, T4 (33 ºC) as control. The treatments were arranged in Randomized Complete Design (RCD) with four replications. All the treatments received the same nutrient concentrations. The experiment layout and fertigation were followed as mentioned in Al Rawahy et al. (2018).

Parameters such as plant height (cm), leaf number/$m^2$, leaf area index ($cm^2$), chlorophyll (SPAD values), fruit number/$m^2$, yield (t/gh), shoot fresh weight (g), root fresh weight (g), shoot dry weight (g), root dry weight (g), shoot dry weight (%), root dry weight (%), fruit length (cm), fruit diameter (cm) and total soluble solids (TSS) (%) were measured besides nutrient elements in shoots and roots including N, P, K, Ca and Mg (AOAC, 1984) determined on dry matter basis. Analysis of variance (ANOVA) and multiple comparisons (least significant difference-LSD) were performed using GenStat $12^{th}$ edition (VSN Intentional, 2011)

## 3. Results

### *3.1 Growth Parameters*

#### 3.1.1 Plant height

Plant height varied from 141 cm to 173.4 cm and from 132 cm to 157.4 cm in 2016/2017 and 2017/2018, respectively, during summer (June-August) with significant ($p < 0.05$) differences among root-zone temperatures(RZT) (Table 1). The cucumber plants in the cooled root-zone temperatures 22 ºC, 25 ºC and 28 ºC produced significantly highest ($p < 0.05$) plant height as compared to that in control (non-cooled root-zone temperature, 33 ºC) in both years. The highest plant height was found at cooled root-zone temperature of 22 ºC to the extent of 173.4 cm followed by 170.3 cm at cooled root-zone temperature of 28 ºC whereas the lowest plant height was found at 33 ºC (141cm) in 2016/2017 ($p > 0.05$). The response trend was not the same in 2017/2018 where the plants at 22 ºC produced higher plant height (157.4) cm followed insignificantly by that at 25 ºC (157.5 cm) and it was significantly the lowest at 33 ºC (127 cm).

#### 3.1.2 Leaf Number

Significant ($p < 0.05$) differences were observed in leaf number per plant between the root-zone temperatures in both years, 2016/2017 and 2017/2018. During the first year leaf number per plant ranged from 27 to 30 whereas in the second year it varied from 29 to 34 (Table 1). The plants at 22 ºC and 25 ºC gave more number of leaves per plant (30 and 29) whereas the lowest number was found at 33 ºC (27) during the first year. Same trend was observed in second year with cooled root-zone temperatures except for root-zone at 28 ºC in which the lowest leaf number was observed (29). Significantly higher number of leaves per plant was recorded with root-zone temperatures 22 ºC and 25 ºC (34 leaves per plant) as compared to that at other root zone temperatures.

Table 1. Effect of root-zone temperature (RZT) on plant height and leaf number/plant of cucumber grown under hydroponic closed system during summer (June-August) in cooled greenhouse

| RZT (ºC) | Plant height (cm) | | Leaf Number/Plant | |
|---|---|---|---|---|
| | First year 2016/2017 | Second year 2017/2018 | First year 2016/2017 | Second year 2017/2018 |
| 22 | 173.4 a | 157.4 a | 30 | 34 |
| 25 | 155 b | 157.5 a | 29 | 34 |
| 28 | 170.3 a | 132 b | 28 | 29 |
| 33 | 141 c | 127 b | 27 | 30 |
| *Statistical Parameters* | | | | |
| F-test | ** | ** | ** | ** |
| LSD (5%) | 12.2 | 10.9 | 1.3 | 1.1 |
| CV % | 17.2 | 6.9 | 10.6 | 8.1 |

### 3.1.3 Leaf Area (cm$^2$)

Leaf area of any plants reflects to amount of photosynthesis and assimilations rates. Leaf area in 2016/2017 and 2017/2018 was higher in all the cooled root-zone temperatures tested as compared to control with significant($p < 0.05$) differences. Leaf area was higher in the second year 2017/2018 among the root-zone temperatures. The leaf area varied from 205.1 to 346.9 cm$^2$ and from 207 to 356.6 cm$^2$ during 2016/2017 and 2017/2018, respectively. Leaf area was in general higher at the root-zone temperature of 22 ºC in both years (346.9 cm$^2$ and 356.6 cm$^2$) and lowest area was at non-cooled root-zone temperature, 33 ºC (205.1 cm$^2$ and 207.0 cm$^2$) (Figures 1a and b).

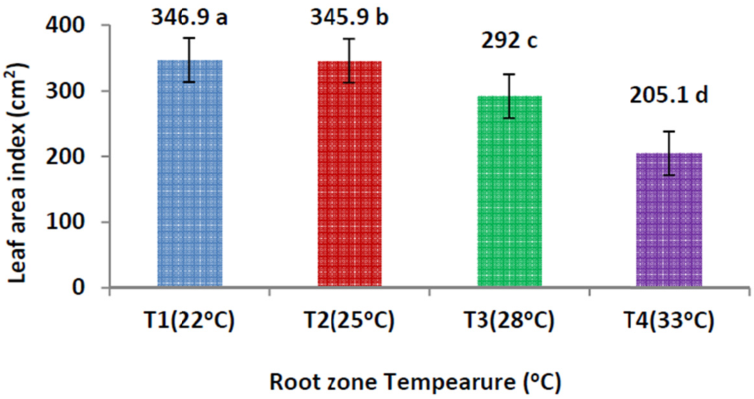


Figure 1a. Effect of root-zone temperature (RZT) on leaf area (cm$^2$) at vegetative stage of cucumber plants grown hydroponically during summer (June-August) 2016/2017

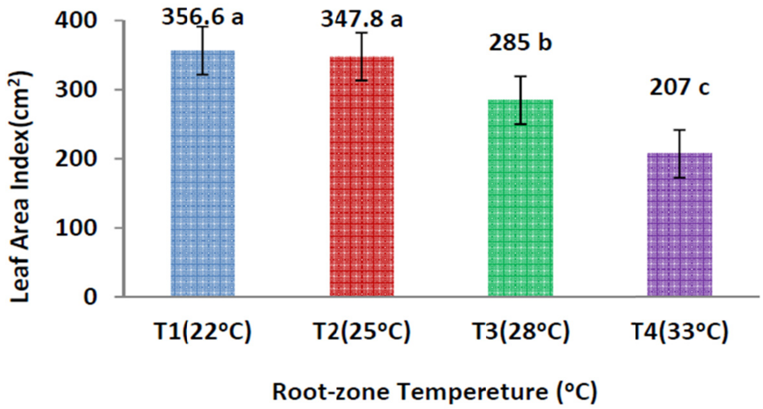


Figure1b. Effect of root-zone temperature (RZT) on leaf area (cm$^2$) at vegetative stage of cucumber plants grown hydroponically during summer (June-August) 2017/2018

### 3.1.4 Chlorophyll Content

Color pigmentation in plants, especially in the form of chlorophyll, is important for their plant growth and development. Significant ($p < 0.05$) differences were observed in chlorophyll content as SPAD values between root-zone temperatures of cucumber in both years, 2016/2017 and 2017/2018. In 2016/2017, chlorophyll content varied from 43 to 48 SPAD values whereas in the second year it ranged from 43.1 to 49.1 SPDA values. Plants at root-zone temperatures of 22 ºC and 25 ºC produced higher chlorophyll content in both years of experiments as compared to root-zone temperature of 28 ºC and control (33 ºC) which were fluctuating and inconsistent. Highest chlorophyll content was given by plants of cooled root-zone temperature of (25 ºC) with 48 SPAD values followed by plants of root-zone temperature of (22 ºC; 45.3 SPAD values). The lowest was given by plants of cooled root-zone temperature of 28 ºC (43 SPAD values) in 2016/2017 (Figure 2a). Same trend was observed in 2017/2018 where plants of cooled root-zone temperatures at 22 ºC and 25 ºC produced higher chlorophyll content as compared to the plants of control. Plants at root-zone temperature of 22 ºC gave the highest chlorophyll content with 49.1 SPAD values followed by the plants at root-zone temperature of 25 ºC (47.4 SPAD values) and the lowest chlorophyll content was found in the control (33 ºC) with 43.1 SPAD values (Figure 2b).

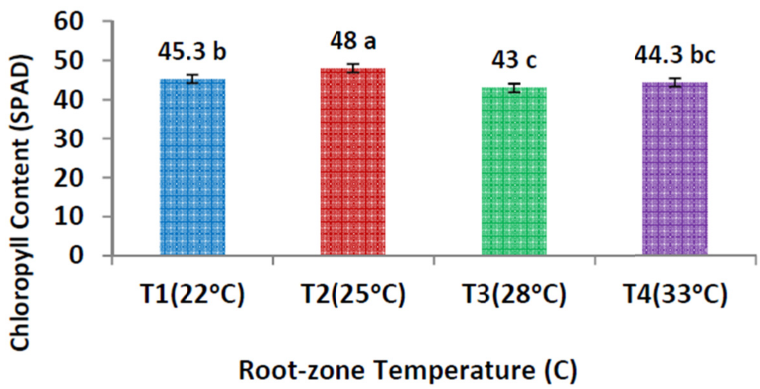


Figure 2a. Effect of root-zone temperature (RZT) on chlorophyll content as SPAD values of cucumber plants grown hydroponically during summer (June-August) first year 2016/2017

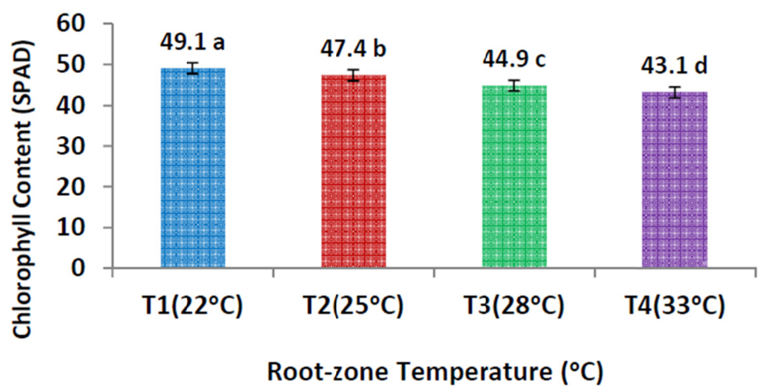


Figure 2b. Effect of root-zone temperature (RZT) on chlorophyll content as SPAD values of cucumber plants grown hydroponically during summer (June-August) second year 2017/2018

### 3.1.5 Fruit Number per $m^2$

Fruit number varied from 101 to 180 with significant ($p < 0.05$) differences between the root-zone temperatures tested in the first year, 2016/2017. All the plants of cooled root-zone temperatures 22 ºC, 25 ºC and 28 ºC produced higher number of fruits compared to plants at control 33 ºC. The highest fruit number per $m^2$ was produced by plants of cooled root-zone temperature of 22 ºC (180/$m^2$) followed by the plants at 28 ºC (178/$m^2$) and the lowest was found at control (33 ºC) (101/$m^2$) (Table 2). With regard to second year 2017/2018, the results showed same trend with increased number of fruits/m$^2$ at tested treatments. Fruit numbers varied from 133 to 221 with significant ($p < 0.05$) differences between all the root-zone temperatures. Plants of cooled root-zone temperatures of 22 ºC, 25 ºC and 28 ºC produced higher fruit numbers/m$^2$ as compared to plants in control. Plants of cooled root-zone temperature of 25 ºC gave the highest fruits number of 221/m$^2$ followed by plants at cooled root-zone temperature of 22 ºC (220/m$^2$) as compared to those in control with 133/m$^2$ (Table 2).

#### 3.1.6 Yield (t/gh)

Significant ($p < 0.05$) yield differences were observed between the root-zone temperatures in cucumber in both years of experiment, 2016/2017 and 2017/2018. However, all the plants of cooled root-zone temperatures; 22 ºC, 25 ºC and 28 ºC produced higher yield as compared to plants in control. The yield varied from 2.8/gh to 5.0 t/gh during the first year 2016/2017. The highest yield was produced by plants of cooled root-zone temperature of 22 ºC with 5.0 t/gh followed by the plants at root-zone temperature of 28 ºC with 4.7 t/gh as compared to those in the control which was the least (2.8 ton/gh). In the second year the results showed the same trend as first year with improved yield of plants in all treatments tested. The cucumber yield ranged between 3.5 t and 6.1 t/gh with significant differences ($p < 0.05$) between the root-zone temperatures. Highest yield was produced by plants at root-zone temperature of 22 ºC (6.1 t/gh) followed by the plants at root-zone temperature of 25 ºC (6.0 t/gh) and 28 ºC (3.8 t/gh) as compared to that in the control (33 ºC) with 3.5 t/gh which was the least (Table 2). The increase in yield in the second year 2017/2018 was attributed more numbers of harvests made and lesser incidences of diseases and pest infestations than those in the first year. In general during summer season the production of cucumber would be normally low due to high temperatures. In the present experiment, on the contrary the cooled nutrient solutions tested had demonstrated to offer positive effects with the higher levels of production as compared to the production level in the non-cooled control.

Table 2. Effect of RZT on Fruit number/m$^2$ and yield (t/gh) of cucumber grown in hydroponics, closed system during summer (June-August) in cooled greenhouse

| RZT (ºC) | Fruit number/m$^2$ | | Yield (t/gh) | |
|---|---|---|---|---|
| | First year 2016/2017 | Second year 2017/2018 | First year 2016/2017 | Second year 2017/2018 |
| 22 | 180 a | 220 a | 5.0 a | 6.1 a |
| 25 | 167 a | 221 a | 4.4 a | 6.0 a |
| 28 | 178 a | 143 b | 4.7 a | 3.8 b |
| 33 | 101 b | 133 b | 2.8 b | 3.5 b |
| *Statistical Parameters* | | | | |
| F-test | ** | ** | ** | ** |
| LSD (5%) | 44.5 | 53.0 | 1.2 | 1.5 |
| CV % | 18.5 | 19.1 | 18.5 | 20.3 |

#### 3.1.7 Shoot Fresh Weight

The effects of cooled root-zone temperature on shoot fresh weight of cucumber plants were highly significant ($p < 0.05$) among the treatments tested in the first year, 2016/2017. Plants of cooled root-zone temperature of 22 ºC and 25 ºC produced higher shoot fresh weight as compared to the plants of non-cooled control with root-zone temperature of 33 ºC. The shoot fresh weight ranged from 188.1 g to 274.2 g. The plants of cooled root-zone temperature of 25 ºC gave 274.2 g/plant followed by plants of root-zone temperature of 22 ºC with 264.1 g as compared to that in control with 188.1g (Table 3). With respect to second year, 2017/2018, no significant differences were observed in shoot fresh weight between the tested root-zone temperatures. Shoot fresh weight ranged from 208.8 g to 256.6 g with the highest shoot fresh weight at cooled root-zone temperature of 25 ºC (256.6 g) followed by that at 22 ºC (227.5 g) as compared to the lowest of 208.8 g at control 33 ºC (Table 3).

#### 3.1.8 Root Fresh Weight

The response of plants in terms of root fresh weight was similar in trend to that shown in terms of shoot fresh weight. Significant ($p < 0.05$) root fresh weights were obtained among the plants of cooled root-zone temperatures and those in control in the first year, 2016/2017. Plants at cooled root-zone temperature of 22 ºC gave the highest root fresh weight (38.0 g) followed by 25 ºC with 36.9 g and the least fresh root weight was at the control with 28.9 g (Table 3). During the second year, 2017/2018 no significant differences were observed in root fresh weight between the treatments (Table 3).

3.1.9 Shoot Dry Weight

Shoot dry weight varied from 37.1 g to 49.3 g with significant ($p < 0.05$) differences among the root-zone temperatures tested. Plants of cooled root-zone temperatures 22 ºC, 25 ºC and 28 ºC gained more shoot dry weight than plants at non-cooled root-zone temperature of 33 ºC (control) in the first year, 2016/2017. Plants of cooled root-zone temperature 25 ºC gave the highest shoot dry weight (49.3 g) followed by root-zone temperature 22 ºC (48.7 g). The lowest shoot dry weigh of 37.1 g was recorded at non-cooled root-zone temperature of 33 ºC (Table 4). In the second year, 2017/2018, shoot dry weight showed no any significant differences among the treatments tested (Table 4).

3.1.10 Root Dry Weight (g)

Significant ($p < 0.05$) effects of root-zone temperatures were noted in root dry weights in both the years. Plants of cooled root-zone temperatures showed more root dry weight than those at non-cooled root-zone temperature (control) in the first year 2016/2017. Root-zone temperature of 22 ºC produced highest root dry weight (20.2 g, 19.9 g) followed by root-zone temperature of 25 ºC (19.9 g, 19.6 g) in 2016/2017 and 2017/2018 respectively whereas the lowest root dry weight was found at non-cooled root-zone temperature of 33 ºC (control) (Table 4).

Table 3. Effect of RZT on shoot and root fresh weight (g) of cucumber grown in hydroponics, closed system during summer (June-August) of 2016/2017 and 2017/2018 in cooled greenhouse

| Root-zone temperatures (ºC) | Year 2016/2017 | | Year 2017/2018 | |
|---|---|---|---|---|
| | Shoot | Root | Shoot | Root |
| 22 | 264.1 a | 38.0 a | 227.5 | 39.5 |
| 25 | 274.2 a | 36.9 a | 256.6 | 36.0 |
| 28 | 222.0 b | 34.8 b | 197.5 | 34.2 |
| 33 | 188.1b | 28.9 b | 208.8 | 31.1 |
| *Statistical Parameters* | | | | |
| F-test | ** | ** | NS | NS |
| LSD at 0.05 | 60.9 | 7.4 | - | - |
| CV % | 16.7 | 14.0 | 33.5 | 26.1 |

Table 4. Effect of RZT on shoot and root dry weight (g) of cucumber grown in hydroponics, closed system during summer seasons (June-August) of 2016/2017 and 2017/2018 in cooled greenhouse

| Root-zone temperatures (ºC) | Year 2016/2017 | | Year 2017/2018 | |
|---|---|---|---|---|
| | Shoot | Root | Shoot | Root |
| 22 | 48.7 a | 20.2 a | 34.7 | 19.9 a |
| 25 | 49.3 a | 19.9 a | 35.7 | 19.6 a |
| 28 | 39.8 b | 17.6 b | 31.7 | 13.6 c |
| 33 | 37.1b | 16.6 b | 29.0 | 17.5 b |
| *Statistical Parameters* | | | | |
| F-test | ** | ** | NS | ** |
| LSD at 0.05 | 3.4 | 1.3 | - | 4.7 |
| CV % | 5 | 4.4 | 17.8 | 17.2 |

*3.2 Nutrient Content*

3.2.1 Nutrient Concentration and Uptake in Shoot

Concentration and uptake of mineral elements in the shoot of cucumber were strongly affected by the interacting effects of root-zone temperature (RZT). Nevertheless, not all elements were affected to the same extent. Significant ($p < 0.05$) increases in nitrogen and calcium uptake were observed between the root-zone temperatures in cucumber shoots whereas there were no significant ($p > 0.05$) effects in uptake of phosphorus, potassium and magnesium elements between the root-zone temperatures in the first year 2016/2017. Nitrogen uptake was increased significantly with the cooled root-zone temperature of 22 ºC, 25 ºC and 28 ºC as compared to that at non-cooled root-zone temperature of 33 ºC. Higher nitrogen concentration was found at root-zone temperature of 22 ºC (3.1%) and 25 ºC (3.0%) where the lowest nitrogen uptake was in non-cooled root-zone temperature of 33 ºC (2.5%). On the other hand, shoot had higher calcium concentration at cooled root-zone temperature of 25 ºC with 4.1% than that at root-zone temperature of 22 ºC with 3.9% while the lowest was that at non-cooled root-zone temperature of 33 ºC with 3.1%. There were significant ($p < 0.05$) effects during second year, 2017/18 in nitrogen, potassium and calcium uptakes in cucumber shoots among cooled root-zone temperatures as compared to those at control. Similar trend however, was observed in all the elements as during first year in respect of nitrogen, potassium and calcium uptakes, which were higher in cooled root-zone temperatures of 22 ºC, 25 ºC and 28 ºC as compared to that non-cooled root-zone temperature of 33 ºC. Highest nitrogen uptake was found in cooled root-zone temperature of 22 ºC 3.4% followed by 25 ºC with 3.0% and 28 ºC with 3.0%. Potassium uptake was higher at cooled root-zone temperatures of 22 ºC, 25 ºC and 28 ºC with 3.1%, 2.9% and 2.6%, respectively (Figure 3a). No any significant effects were observed in phosphors and magnesium uptakes in all the root-zone temperatures during 2017/2018 (Table 3b). The results obtained indicated that concentrations of all nutrients elements in shoots at the end of the experiment were of lower magnitude as compared those at the initial stages of growth as all nutrient elements were accumulated in leaves and fruits of cucumber.

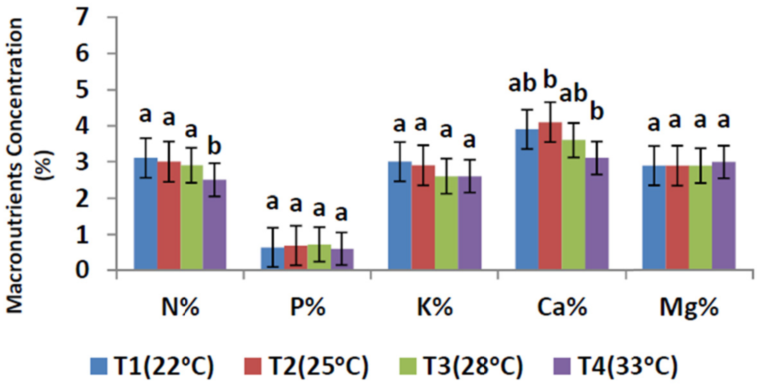


Figure 3a. Effect of root-zone temperatures on shoots nutrient concentration of cucumber plant grown in hydroponic closed system during summer (June-August) in 2016/2017

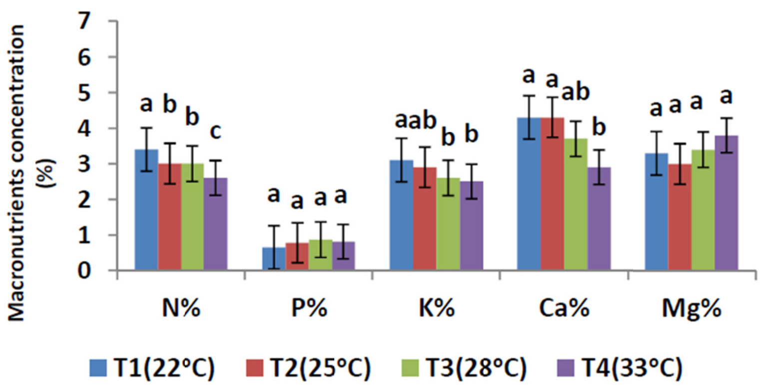


Figure 3b. Effect of root-zone temperatures on shoots nutrient concentration of cucumber plant grown in hydroponic closed system during summer (June-August) in 2017/2018

### 3.2.2 Nutrient Concentration and Uptake in Root

Significant ($p < 0.05$) nutrients element concentrations' uptakes were obtained in all the root-zone temperatures in cucumber roots in the first year. Nitrogen uptake was found significantly increased with cooled root-zone temperatures. The highest nitrogen uptake was found at cooled root-zone temperature of 22 ºC with 2.7% and 25 ºC with 2.7% as compared to the lowest uptake recorded at non-cooled root-zone temperature of 33 ºC (2.3%).

Similar trend was seen in potassium and magnesium uptakes (Figure 4a). With regard to second year 2017/2018, the nutrient elements showed significant ($p < 0.05$) uptake effects in roots of cucumber between the root-zone temperatures except for calcium element. The highest nitrogen uptake was found at cooled root-zone temperature of 22 ºC (2.9%) followed by cooled root-zone temperature of 25 ºC (2.8%) as compared to that of 28 ºC with 2.6%. The lowest was found at non-cooled root-zone temperature of 33 ºC (2.3%). Similar trends were noticed for phosphorus, potassium and magnesium uptakes. There were no significant effects in calcium uptake in roots of cucumber between the root-zone temperatures. The results thus indicated that concentrations of all nutrients elements in roots at the end of the experiment were lower as compared to those at the initial stages as all nutrient elements were accumulated in leaves and fruits of cucumber (Figure 4b).

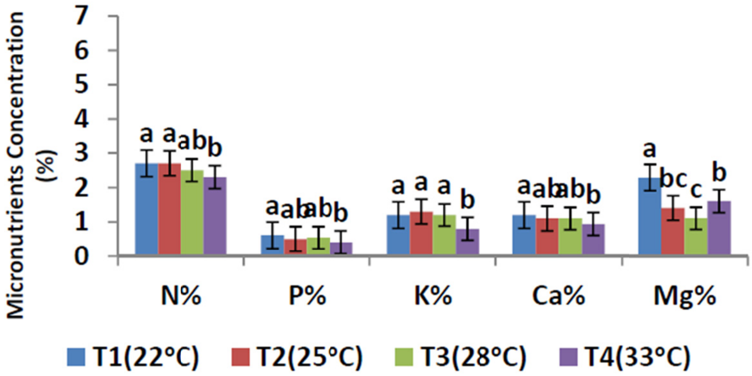


Figure 4a. Effect of root-zone temperatures on roots nutrient concentration of cucumber plant grown in hydroponic closed system during summer (June-August) in 2016/2017

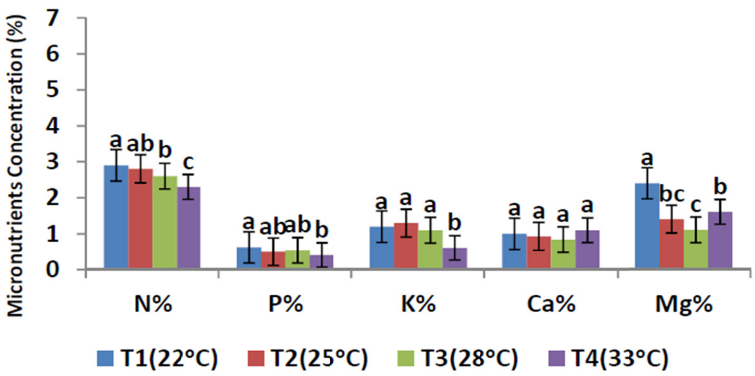


Figure 4b. Effect of root-zone temperatures on roots nutrient concentration of cucumber plant grown in hydroponic closed system during summer (June-August) in 2017/2018

## 4. Discussion

The present study intends to comprehend the effects of root zone temperatures (RZT) on the growth and development of cucumber plants to ultimately increase the cucumber fruit production in terms of yield and yield related characters, which are discussed here under:

### *4.1 Plant Height*

The cucumber plants responded significantly ($p < 0.05$) highest to the cool root zone temperatures of 22 ºC and 25 ºC at root zones in both years 2016/17 and 2017/18 during summer season which coincides from June to August in Oman as well as all the countries of Arabian Peninsula. Differences in response of cucumber plants from two years in plant height at different root-zone temperatures at different stages of growth of the crop were similar to the study of Moon et al. (2007) where it was observed that during summer the growth rate of the stem of cucumber at both temperatures had been linear for a long time in contrast to the exponential growth found in winter while in autumn and spring the growth rate at 25 ºC was linear. Growth indexes plant height, internode length, root length, and leaf area at low RZT had less difference among nutrient treatments. However, greater response was obtained for different nutrients at high RZT. Yan et al. (2013) showed that root-zone cooling did not affect the plant height, number of nodes, and stem weight. Sakamoto and Suzuki (2015) found that root-zone heating at 33 ºC reduced leaf number, shoot length of carrots plants. Veenman and Zoneh (1977) demonstrated that plants of tomato grown at the lowest and the highest root temperatures were fully normal in appearance although their size was smaller than at the optimal temperatures of 20 ºC and 25 ºC (Table 1).

*4.2 Leaf Number/Plant*

As indicated in the results, there were significant ($p < 0.05$) differences in leaf number /plant in both years between the cooled root-zone temperatures of 22 ºC, 25 ºC and 28 ºC and non cooled root-zone temperature of 33ºC (control). Veenman and Zoneh (1977) reported that the seasonal effect on leaf number of tomato was much smaller as compared that on plant height. At a root temperature of 25 ºC, after 25 days of transplanting, plant height in summer was 42.5 cm and 9 cm in winter while leaf number was 14.0 and 8.3 in summer and winter, respectively. No apparent interaction between season and root temperature was observed in leaf number, as was the case with plant height since leaf number was found increased linearly with time. The effect of RTZ on number of leaves /plant was clear at 22ºC in which the plants produced the highest leaf number in both years, 2016/2017 (30) and 2017/2018 (34) followed by those at 25 ºC (29 and 34) as compared to that at control (27 and 30). The results obtained in the present study are in agreement with Sakamoto and Suzuki (2015) who found that root-zone heating at 33ºC reduced leaf number and shoot length of carrots plants. Similarly, Moon et al. (2007) revealed that leaves and stem height had slow growth rate as root-zone temperature was increased after 7 and 14 days of planting. Further, Masaru et al. (2016) on strawberry showed that the number of newly emerging leaves was found increased in plants cooled at root zone.

*4.3 Leaf Area (cm$^2$)*

The results of the present study indicated significant ($p < 0.05$) effects in leaf area between plants of cooled RZT of 22 ºC, 25 ºC and 28 ºC with higher leaf area in comparison with non-cooled RZT 33 ºC (control) in both years 2016/2017 and 2017/2018. This could be due to the fact that RZT influences the vegetative growth and biomass of the plant (Zhang et al., 2008; Chadirin et al., 2011; Sakamoto & Suzuki, 2015a, 2015b) and leaf area is indirectly associated with the rate of photosynthesis and amount of assimilation rate in the plants (Pang et al., 1997; Lu et al., 1994). Yan et al. (2013) reported that strong interactions were observed between RZT and nutrients on leaf area and concluded that higher biomass and growth of cucumber seedlings were produced at RZT of 20 ºC. Further, Xiaolei and Zhifeng (2004) found that optimal LAI from 3 to 3.5 could balance the photosynthetic capacity per unit area, light penetration and air circulation and could increase the yield in plastic greenhouse. On the contrary, in respect of the effect of higher RZT, it was found that leaves of cucumber at 35 ºC root-zone temperature(RZT) were severely affected with small area and burn in plants (Moon et al., 2007).

*4.4 Chlorophyll Content*

In the present study, the results showed significant effects of the RZT on chlorophyll content as SPAD values in both years. Higher values were linked to lower RZT viz. 22 ºC to 28 ºC. Many studies revealed that high temperature can affect physiological process such as chlorophyll content and subsequently metabolism of plant. Heat stress not only causes an imbalance in plant metabolism and disruption of cellular homeostasis resulting in deleterious damage to plant cells (Suzuki & Mittler, 2005) but also triggers significant alternations in plant physiological processes, such as water uptake and leaf photosynthesis (Suzuki et al., 2008; He et al., 2013). Masaru et al. (2016) found that high RZT treatment induced plants withering within two months or decreased the chlorophyll content as expressed by the SPAD value.

*4.5 Fruit Number/m$^2$*

Cooling of RZT of cucumber significantly showed positive effect in fruit numbers/m$^2$ in both years, 2016/2017 and 2017/2018 as compared to non-cooled control. Moon et al. (2007) found that severe growth and development inhibition by high temperature in summer in cucumber. High temperature in a greenhouse during summer inhibits crop growth especially high RZT accompanied with high air temperature (Song, 2013). The highest fruit number/m$^2$ was produced by plants of cooled RZT and the lowest was given by non-cooled RZT. Our findings are in agreement with those of Moon et al. (2007) who reported that the number of fruits per plant was 15.9 in non-cooled root-zone and 19.3 in cooled root-zone.

*4.6 Yield*

The results of present study indicated that cooled nutrient solution temperatures that reflect root-zone atmosphere of cucumber during summer season can improve the growth as well as the yield of cucumber. It is well understood that environmental stress can affect plant development; growth and yield. Root-zone temperature is the important factor which can affect plant growth, yield, uptake of water and nutrient uptake

(Stoltzfus et al., 1998; Lahti et al., 2005; Solfjeld & Johnsen, 2006; Diaz-Perez et al., 2007). In the present study all the plants of cooled RZT 22 ºC, 25 ºC and 28 ºC produced higher yield as compared to plants of non-cooled RZT, 33 ºC in both years 2016/2017 and 2017/2018. Our results are in agreement with Moon et al. (2007) who found the most remarkable effect of root-zone cooling in terms of increase in yield of cucumber as compared to cucumber grown in non-cooled root-zone. Similarly, Lee (1994) reported that as the plants grow, the fruit yield of cucumber proportionally decreases with increased root-zone temperature. However, these results are in contrast to those of Gent and Ma (1998) who obtained better yield of tomato by using a forced-air heater applied to root-zone for several regimes of daily temperature. Urrestarazu et al. (2008) revealed that lesser effects were observed at root-zone temperature between 18-22 ºC concerning yield and fruit quality parameters in rockwool grown melon. Number of fruits and fruit size (fresh weight) of strawberry tended to increase by root-zone cooling treatments (Sakamoto et al., 2016). Mawgoud et al. (2005) revealed positive effect of heating on production of pepper with 39% to 76% increases in yields due to an increase in both fruit number and average fruit weight. The vegetative growth was improved by increasing leaf area and plant height in cooled plants as compared to non-cooled ones with increase in fruit yield (Fujishige et al., 1991; Nkansah & Ito, 1994). In addition, Sasaki and Itagi (1989) reported that fruit yield was increased by root-zone cooling at 20 ºC in summer tomato production. Lee (1996) reported that yield of cucumber fruits was highest from March to June, and from September to November but lowest in summer and winter season, especially in July and August in Korea. Similarly, Lee (1994) and Du and Tachibana (1994a, 1994b) revealed that high temperature in summer and low temperature in winter are the main factors in reducing productivity in the year-round cultivation of cucumber. The authors reported that below 12-13 ºC RZT, growth was suspended and over 35 ºC RZT, growth was inhibited. In Oman, low yields in summer have been reported during May- July period of the year according to the report of the Public Authority for Civil Aviation Authority (PACA, 2016) and reports from other Arabian Peninsula countries. The present findings suggested that cooled root-zone of cucumber through cooled nutrient solution temperature increased yield of cucumber during summer.

### *4.7 Shoot & Root Fresh Weight*

Although suboptimal root-zone temperature tends to restrict plant growth, responsiveness of plants to root-zone temperature depends on the plant species. For instance, six cucurbitaceous species exhibited different responses in the form of changes of biomass, photosynthesis, and stomatal conductance at RZT between 14 ºC and 34 ºC (Zhang et al., 2008). In the present study, cool RZT had positive effects on both shoot and root fresh weights in both the years although second year was not significant. Similar results were proved by Daskalaki & Burrage (1997) who found that shoot fresh weight was the highest at 28 ºC and lowest at 12 ºC whereas in other study with muskmelon, it was reported that plant fresh weight gain was the highest at the 25 ºC RZT (Rhonda & Stoltzfus, 2008). Adebooye et al. (2009) observed that RZT of 20 ºC and 25 ºC produced significantly ($p \leq 0.05$) increased effects on the average number of tendrils, number of leaves, fresh leaf weight, stem length, fresh stem weight, root length, fresh root weight and root volume as compared to those at 30 ºC. Recently, Sun et al. (2016) reported that RZ cooling increased shoot fresh weight, root fresh weight, shoot dry weight, root dry weight, total plant fresh weight, and total plant dry weight in lettuce by 8.9, 20.5, 7.8, 14.3, 9.7, and 8.5%, respectively.

### *4.8 Shoot & Root Dry Weight*

The results of the present study showed similar response of cucumber plants to cooled RZT in terms of shoot and root dry weigh as shown in terms of shoot and root fresh weights. Plants at cooled RZT of 25 ºC and 22 ºC produced higher shoot and root dry biomass as compared to non-cooled root-zone temperature of 33 ºC in both years although shoot dry weight was not significant in second year. James et al. (2008) found that root and shoot dry weight, rate of shoot growth, plant height, and water use peaked at 25 ºC. Yan et al. (2013) reported that plant dry weights were suppressed at low RZT of 12 ºC while higher biomass and growth of cucumber seedlings were produced at elevated RZT of 20 ºC under each nutrient treatment. Growth indexes (plant height, internode length, root length, and leaf area) at 12 ºC-RZT had less difference among nutrient treatments but greater response was obtained for different nutrients at high RZT. Sun et al. (2016) demonstrated the feasibility of cultivating hydroponic lettuce in high-temperature season through cooling of the nutrient solution. Similarly, the results obtained by other researchers (Zhang et al., 2008; Chadirin et al., 2011; Sakamoto & Suzuki, 2015a, 2015b) showed the positive influence of root zone temperature on both the vegetative growth and biomass of the plant similar to the results of the present study.

### *4.9 Nutrients Concentration and Uptake in Shoot and Root*

Mineral nutrition of plants plays a crucial role in increasing resistance to environmental stresses (Marschner, 1995). In the present study, responses of shoots and roots to root-zone temperatures (RZT) were significantly (p

$< 0.05$) affected by cooled RZT at 22 ºC, 25 ºC and 28 ºC as compared to uncooled RZT 33 ºC in both years, 2016/2017 and 2017/2018. The concentration and uptake of mineral elements in the cucumber shoot and root were strongly affected by the interacting effects of root-zone temperature (RZT). Nevertheless, not all elements were affected to same extent. Total N, P, K, Ca, and Mg uptakes were found promoted at RZT of 22 ºC, 25 ºC and 28 ºC as compared to that in non-cooled RZT of 33 ºC. This was also noted by earlier researchers. The shoot and roots mineral element uptake was increased with elevated root temperature which promoted plant nutrient uptake by (1) increasing new root formation (Daskalaki & Burrage, 1997; Domisch et al., 2002), (2) changing root physiology and improving nutrient uptake (Carey & Berry, 1978; Marschner 1990; Kozlowski & Pallardy, 1997), and (3) accelerating nutrient mineralization in soil (Domisch et al., 2002). Wan et al. (1999) reported that the root growth of trembling aspen seedlings at 10 ºC was lower than that at 20 ºC soil temperature. The higher nutrient distribution ratio in shoots at 20 ºC-RZT resulted in increased stem growth and higher shoots nutrients concentrations (Lahti et al., 2005). Yan et al. (2012) found that differences in nutrient uptake were existed between species as affected by RZT such as increasing solution temperature at 14 ºC and 20 ºC in cucumbers which showed an increased $NO_3$ uptake with no effect on phosphate uptake as compared to unheated treatment. Urrestarazu et al. (2008) reported that increasing nutrient solution temperature to 18-22 ºC increased phosphate uptake in two substrates in cucumber. In the present study, significant effect of phosphate uptake was observed in all the cooled RZT as compared to non-cooled RZT in the roots while no significant effect was observed in shoot of cucumber plant in both years. The results of the present study indicated that cooled nutrient solution temperature had positive effect on shoot and root growth and nutrient uptake. In this respect, Rhonda et al.(2008) reported that root P and Zn concentrations increased linearly with increasing RZT while Daskalaki and Burrage (1998) showed that uptake of all nutrients (N, P, calcium (Ca), and K) could be promoted significantly when root temperature was increased from 12 ºC to 20 ºC in cucumber. Hood and Mills (1994) also found RZT of 22 ºC produced higher growth and nutrient uptake in snapdragon (*Antirrhinum majus* L. Peoria') as compared to that of 8 ºC and 15 ºC. Similarly, with regard to potassium the crop was found responding positively at cooled RZTs than that of non-cooled RZT in uptake of potassium in shoots and roots of cucumber. In the present study, cooled RZT at 22 ºC and 25 ºC accumulated more potassium as compared to non-cooled RZT of 33 ºC athough it was not significant effect in root potassium uptake in second year. These findings are in line with Gosselin and Trudel (1983) who demonstrated that raising the RZT to 24 ºC increased the shoot P and K concentrations in tomato as compared to those at 12 ºC or 15 ºC. Cooling of root-zone temperature did not significantly affect magnesium concentrations and uptake. Tan et al. (2006) showed that total shoot and root $NO_3$, K, Ca, Cu, Fe, Mg, Mn, and Zn accumulation of 20 ºC-RZT plants were more than the plants having RZT more than 20 ºC which suffered from a reduction of total mineral accumulation. Similar trend was noticed in our study in respect of shoot and root calcium uptake which was positively influenced by cooled RZTs with significant ($p < 0.05$) differences. Yan et al. (2012) demonstrated that more nutrients are accumulated in roots and less is transported to shoots at 10 $^0$C-RZT as compared to those at 20 ºC-RZT, which are similar to our observations. James et al. (2008) demonstrated that uptake of all mineral elements was significantly different with each temperature treatment except for B, Fe, and Mo which did not respond to temperature.

## 5. Conclusion

It is concluded that high air temperature and root-zone temperatures (RZT) in summer season can suppress or decrease the biomass, nutrient uptake and growth of cucumber. The results showed that the cooled root-zone temperatures (RZT) of 22 ºC and 25 ºC improved growth characters (plant height, leaf number, chlorophyll content, leaf area) and uptake of nutrients. The productivity of cucumber was found increased at cooled RZT of 22 ºC by 74.3% and at 25 ºC by 71.4% as compared to the yield at non-cooled RZT of 33 ºC. Therefore, cooling of root-zone temperatures through nutrient solution is very essential during summer period for improved yield in cucumber.

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