Growth Response of Greenhouse-Produced Muskmelon and Tomato to Sub-Surface Drip Irrigation and Soil Aeration Management Factors

Yuan Li

Shaanxi Normal University

Wenquan Niu (✉ nwq@vip.sina.com)

Northwest Agriculture and Forestry University <https://orcid.org/0000-0001-6884-1699>

Xiaoshu Cao

Shaanxi Normal University

Mingzhi Zhang

Shaanxi Normal University

Jingwei Wang

Northwest Agriculture and Forestry University

Zhenxing Zhang

Northeast Normal University

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Abstract

Background: Hypoxia causes injury and yield loss. Soil aeration has been reported to accelerate the growth of plants and increase crop yield. The aim of this study was to examine growth response of greenhouse-produced muskmelon to 3 levels of sub-surface drip irrigation (I), 3 different installation depths of drip laterals in the soil (D), and 4 levels of supplemental soil aeration frequency (A). A fractional factorial experiment was designed to examine these treatment effects on marketable fresh fruit yield, leaf area index during 3 growth stages, and dry matter partitioning at harvest. In addition, we studied the response of fruit yield and dry matter of tomato to 2 levels of burial depths of subsurface tubing in combination with 3 frequency levels of soil aeration.

Results: Results showed that soil aeration can positively influence the yield, leaf area index, dry matter and irrigation use efficiency of the muskmelon ($p < 0.05$). The fruit yield of muskmelon and tomato were increased by 21.5% and 30.8% respectively with 1-d and 2-d aeration intervals compared with the no aeration treatment.

Conclusions: The results suggest that soil aeration can positively impact the plant root zone environment and more benefits can be obtained with aeration for both muskmelon and tomato plants.

Background

It is well-known that most of mesophytic plant roots require an adequate and continuous supply of soil O_2 in order to respire, grow, develop, and function normally [1]. Previous studies have shown that hypoxia stress limited leaf growth, the rate of leaf expansion declined, and the size of leaf reduced [2]. High CO_2 concentrations (at $2500 \mu L L^{-1}$) or low (10% by volume) O_2 in the root-zone significantly increased the activity of lactate dehydrogenase (LDH), alcohol dehydrogenase (ADH), and pyruvate decarboxylase (PDC) in muskmelon plants, resulting in inhibition of growth, and decrease in fruit yield and quality [3–5].

Sub-surface drip irrigation allows the application of nutrients and other dissolved agri-chemicals directly to the wetted portion of root zone. Supplemental soil aeration is also possible either along with the water (termed as aerated irrigation) or separately, and can effectively improve the oxygen level in rhizosphere. Studies have shown that these practices can be very useful in overcoming problems associated with hypoxia in the root zone of irrigated crops over a range of crops, soil water contents and soil types, and for improving crop performance under oxygen-deficient conditions [6–8]. Aerated irrigation positively affected yield and improved quality for cotton, beans, squash, pumpkin, cucumber, tomato, rice and other crops especially on heavy and saline soils [9–13].

These demonstrated positive effects of aerated irrigation and supplemental aeration on growth and yield have not been completely explained in the literature. It is quite possible that improved LAI of the leaves may be a key mechanism for the increased yield and quality. We suspect that varying the aeration frequency, aeration volume, aeration position and irrigation amount would result in a possible change in rhizosphere soil environment, LAI, and irrigation use efficiency of plants, thus changing the plant growth and fruit output. The specific objective of this study was to determine the response of greenhouse-produced muskmelon and tomato plants on clay loam soils of the semi-arid area of Northwest China under various combinations of sub-surface irrigation volumes, tubing placement depth, and supplemental aeration frequency.

Results

Muskmelon results

LAI of muskmelon

Values in the LAI₂₅ row of Table 4 corresponded to the tendril elongation growth period. The 55 DAT (LAI₅₅) and 75 DAT (LAI₇₅) measurements were taken during the flowering and at fruit harvest. The overall mean of 2.69 at 40 DAT was close to double the value of 1.31 at 25 DAT. At 75 DAT the LAI of 2.86 was only about 4% higher than at 40 DAT. The 10 cm tubing placement depth tended to be significantly lower compared to 25 and 40 cm depth for the 55 and 75 DAT measurements. Differences between the LAI marginal means for irrigation level were non-significant for all 3 sampling dates (Table 4). Among the single-factor analyses, tubing placement depth had a significant impact on both LAI₅₅ and LAI₇₅, aeration frequency had an extremely significant impact on LAI₂₅. The identified significant D x A interaction for LAI₂₅, and A x I interaction for LAI during the tendril elongation growth period and fruit harvest period.

The 1-way ANOVA showed that LAI₂₅ values were all < 2.00 for all treatment combinations (Figure 1). The highest LAI₂₅ value of 1.87 for the D₁₀A₁I₈₀ treatment combination was significantly higher ($P < 0.01$) than all the non-aerated combinations with values < 1.00 (namely D₁₀A_NI₇₀ = 0.81, D₂₅A_NI₈₀ = 0.85, D₄₀A_NI₉₀ = 0.85) regardless of depth and irrigation level. Treatment combinations with daily soil aeration tended to be higher or similar to those with the 2-day and 4-day soil aeration frequency. Combination with D₄₀ and A₄ gave LAI₂₅ < 1 . Combinations with higher A₂ and A₁ aeration frequency and shallower D₂₅ and D₁₀ placement depth gave LAI₂₅ > 1 indicating that lowering placement depth could offset the negative impact of lowering soil aeration frequency (Figure 1).

The highest LAI₅₅ value of 3.60 during the flowering period was obtained for the D₂₅A₁I₉₀. LAI₅₅ values > 3.00 were obtained only for the D₂₅A₄I₈₀ (= 3.22) and D₄₀A₁I₇₀ (= 3.32) treatment combinations. These LAI₇₅ values for these combinations were practically the same as those for LAI₅₅. It would appear that 3.00 to 3.60 may represent the maximum LAI range for the Shantian No. 1 muskmelon cultivar as measured under the experimental conditions.

Except for the D₁₀A_NI₇₀ treatment combination with LAI₅₅ = 1.87, all the 8 remaining combination LAI₅₅ values were between 2.00 and 3.00. For the D₂₅A₁I₉₀ combination, the LAI₅₅ = 3.60 represented a 116 % increase on the LAI₂₅ = 1.66 value. Corresponding increases were 112 % and 154% for the D₂₅A₄I₈₀ and D₄₀A₁I₇₀ treatment combinations. Increases for LAI₅₅ relative to LAI₂₅ tended to be higher for combinations with the lower (A₄ and A_N) soil aeration frequency and especially for the higher irrigation levels (I₉₀) (Table 4). As indicated the LAI₇₅ values were very close to the LAI₅₅ for some combinations indicating little

leaf growth after the flowering and during the fruit enlargement growth stages. LAI₇₅ values were markedly lower than LAI₅₅ for the D₁₀A_NI₇₀ and D₄₀A_NI₉₀ treatment combinations indicating possible earlier senescence.

Dry matter partitioning and irrigation use efficiency of muskmelon

Total dry matter of muskmelon progressively increased with increasing tubing placement depth and progressively decreased with decreasing soil aeration frequency (Table 4). Decreased soil aeration frequency tended to progressively reduce all 3 components of the total DM. The effects were more marked for the leaf and root contributions. The marginal mean for leaf and root DM with daily soil aeration was 50% and 71% higher than the values for no aeration. The corresponding value for stem DM was 32%. The marginal mean for root DM was significantly higher for the I₇₀ irrigation level compared to the I₈₀ and I₉₀ levels. In addition, interaction analysis found that D x A and D x I significantly affected the root DM, D x I and A x I significantly affected the Total DM and Stem DM. Overall mean total DM was 52.2 g per plant partitioned as 11.9 g in stem+ 38.3 g in leaf + 2.0 g in root representing 22.7, 73.4, and 3.9 % respectively. These DM partitioning percentages were similar for each of the tubing placement depths, soil aeration frequencies, and irrigation levels. Values ranged between 21–26%, 68–75%, and 3–4% respectively for the stem, leaf, and root contribution to the total DM for all levels of the treatment factors (Table 4). The D₄₀A₁I₇₀ treatment combination resulted in the maximum plant root, stem, leaf and total DM values (Figure 2). As shown, the plant root, stem, leaf and total DM values for treatment combinations with daily soil aeration tended to be higher than those with the no aeration.

The ternary plot (Figure 3) show the range of the ratios for root, stem, and leaf DM of muskmelon to total post-harvest DM at 75 days after transplanting for each treatment combination. The root DM percentages fell between 2.8 to 5.4%. The leaf DM range was 67.5 to 75.7% and 20.6 to 28.5% for the stem DM. These ranges were quite narrow indicating that the treatment combinations did not markedly affect DM partitioning in the muskmelon plants. Nevertheless, it would be interesting to examine the clusters of treatment combinations at the high and low ends of these ranges as shown in Figure 3. The cluster with high stem DM percentages was D₁₀A_NI₇₀ > D₁₀A₄I₈₀ > D₁₀A₁I₈₀ treatment combinations (Figure 3). The treatment cluster of low leaf DM percentages was D₁₀A_NI₇₀ < D₁₀A₄I₈₀ < D₁₀A₁I₈₀ compared with the cluster of high leaf DM percentages D₂₅A_NI₈₀ > D₂₅A₁I₉₀ > D₄₀A₁I₇₀ treatment combinations. High root DM percentages was obtained for the D₁₀A₄I₈₀ > D₁₀A₁I₈₀ cluster of treatment combinations. These clusters tended to confirm the existence of 2-factor interactions (Table 4).

The overall irrigation use efficiency for marketable fruit yield of muskmelon (IUE_f) across each treatment factor in Table 4 was 17.2 g per plant per liter of total irrigation water applied (subsurface drip + initial 70 mm surface irrigation immediately at prior to transplanting). Neither tubing placement depth nor soil aeration resulted in significant differences in the IUE_f marginal means. The IUE_f marginal mean was 21.5 g fresh fruit per plant per liter for the I₇₀ irrigation level. Corresponding values decreased linearly by 20 % and 40% for I₈₀ (= 17.2) and I₉₀ (= 12.9). These decreases were significantly (p < 0.05) different. The 3-way ANOVA indicated a highly significant 2-factor A x I interaction effect (Table 4).

The overall irrigation use efficiency (IUE_{dm}) for total dry matter (stem + leaf + root) of muskmelon across each treatment factor in Table 4 was 7.58 g per plant per liter of total irrigation water applied. All treatment factors significantly affected IUE_{dm} and all 2-factor interactions were highly significant (Table 4). The IUE_{dm} value for D₄₀ (= 8.94) was significantly higher than for D₁₀ (= 6.15) by 45 %. Similarly, IUE_{dm} progressively increased with increasing aeration frequency from 6.20 for A_N to 6.53, for A₄, to 7.81 for A₂, and 9.75 for A₁. The 57 % increase between the values for A_N and A₁, and the 49 % increase between A₄ and A₁, were significant (P < 0.05). IUE_{dm} values decreased with increasing irrigation level. The marginal mean of 9.23 for I₇₀ differed significantly from to the value of 7.29 for I₈₀ (20 % lower), and 6.20 for I₉₀ (33 % decrease).

Marketable fresh fruit yield of muskmelon

The results in Table 4 show significant treatment main effects for the drip tubing placement depth and soil aeration frequency experimental factors. Increasing depth of tubing tended to decrease the marketable fresh fruit yield per plant in a non-linear manner. Values increased non-significantly from 1.48 to 1.59 kg per plant between the 10 cm to 25 cm tubing placement depth. However, the mean of 1.38 kg per plant for the 40 cm placement depth was significantly lower than for the 25 cm depth (Table 4). Only the D x I two-factor interaction on fresh fruit yield was significant (Table 4) indicating that the tubing placement depth effect would be different for the various irrigation levels. This was due to tubing placement depth determine the position of the soil wetted. Uneven redistribution of soil water in different longitudinal position result in different water use efficiency and fruit yield. It seems that the optimal installation depth of drip pipes is around 25 cm. However, the fractional factorial design does not permit examination of the simple effects of placement depth at each irrigation level.

Yield progressively decreased with decreasing soil aeration frequency from 1.64 kg/plant with daily aeration to 1.51, 1.43 1.35 with 2-day, 4- day, and no aeration, respectively (Table 4). A comparison of means showed that although the daily value was not significantly better the 2-day frequency, it was significantly better than the 4-day and no aeration treatment (Table 4). Irrigation means were not significantly different. Values were 1.53 kg/plant for irrigating to 70% of field capacity and 1.51 and 1.40 kg/plant for the 80% and 90% of field capacity levels (Table 4).

The one-way ANOVA for marketable yield supported the foregoing results. When arranged in descending order, the marketable yield in kg per plant tended to fall into several groups for the 12 treatment combinations (Figure 5). A high-value group comprising in order D₂₅A₂I₇₀ (1.67 kg per plant) > D₁₀A₁I₈₀ (1.65) = D₄₀A₁I₇₀ (1.65) > D₂₅A₁I₉₀ (1.63); an intermediate group D₂₅A₄I₈₀ (1.54) > D₂₅A_NI₈₀ (1.50) > D₁₀A₂I₉₀ (1.48); a low yield group D₁₀A₄I₇₀ (1.40) > D₁₀A_NI₇₀ (1.38) > D₄₀A₂I₈₀ (1.37) > D₄₀A₄I₉₀ (1.34). The lowest yield of 1.16 kg per plant was obtained for D₄₀A_NI₉₀. The high values group included all the high frequency (A₁) soil aeration. The lower frequency aeration (A₂, A₄, A_N) and the higher irrigation level means (I₈₀ and I₉₀) were associated with the low value group. These results tend to confirm a positive effect of soil aeration.

Given a measured 4 to 5 fruits per plant, the foregoing results imply increasing fruit size for the grouping of the treatment combinations. Average fresh fruit weight ranged from 232 to 290 g for the lowest yield of 1.16 ± 0.08 kg for $D_{40}A_N I_{90}$. The range for the low value group average of 1.37 ± 0.20 kg was 275 to 343 g, for the intermediate group with 1.41 ± 0.29 kg was 300 to 376 g, and for the high value group with 1.65 ± 0.43 kg was 330 to 412 g. The overall mean across all treatment factors in Table 4 and treatment combinations was 1.48 kg per plant giving an overall average fresh fruit weight ranging between 300 to 360 g for the Shantian No. 1 cultivar.

Tomato results

Dry matter partitioning of tomato

Figure 4 shows that Post-harvest stem, leaf, and root dry matter of tomato was greater with aeration than without aeration treatment. For both tube burial depths, Post-harvest stem, leaf, and root DM increased with increasing aeration frequency. Maximal values for stem, leaf, and root DM were obtained in the $D_{15}A_2$, $D_{40}A_2$, $D_{40}A_4$ treatments, respectively. Our investigation found that root DM of tomato with a 40-cm burial of the drip irrigation tube was higher than 15-cm treatment. The highest Total dry matter (stem + leaf + root DM) value of 98.4 g was obtained for the $D_{15}A_2$.

Marketable fresh fruit yield of tomato

Soil aeration improved plant root growth environment, thus increasing yield. Figure 6 shows that tomato yield of tomato was greater with aeration than without aeration treatment. For both tube burial depths, tomato yield increased with increasing aeration frequency. The $D_{15}A_2$ treatment combination resulted in the maximum tomato yield (Figure 6). The $D_{15}A_2$ was increased the tomato yield by 27.8% compared with the $D_{10}A_N$.

Discussion

Sub-surface drip irrigated systems are managed to optimize soil water availability, accessibility, and use efficiency for maximum growth and marketable yield. On the other hand, irrigation always results in displacement and/or redistribution of soil air. This can reduce the level and availability of O_2 which is continuously needed to act as the electron acceptor in the tricarboxylic acid metabolic cycle, ATP production, and normal root cell activity [14, 15]. Oxygen-deprivation destroys mitochondria and proteins in root cells leading to cytoplasm acidosis and plant growth inhibition [16]. In this context, it would be expected that any negative growth impact of increasing irrigation application can be offset by soil aeration delivered via the drip-irrigation tubing when placed at a given depth in the soil.

Effect of soil aeration on muskmelon and tomato growth

Hypoxia induces a shift from normal respiration to anaerobic respiration. As reported in previous, hypoxic stress causes an accumulation of leaf abscisic acid, which reduces stomatal density and opening and inhibits the growth of stems and leaves, resulting in slower plant growth, reduced accumulation of dry matter, and limited yield and quality improvement [17]. Chen et al. [7] found that aeration significantly improved dry matter accumulation, yield, and water use efficiency of cotton, wheat, tomato and pineapple in a heavy clay soil. Our results showed that soil aeration had a positive effect on both muskmelon and tomato plant growth. Both muskmelon and tomato DM increased with increasing aeration frequency indicating that rhizospheric oxygen stress do exist, and soil aeration would more likely ameliorate hypoxic conditions.

Applying 405 L of air through the average of 36 emitters would imply soil ventilation at a rate of about 11 L per emitter. It would be expected that most of this air would move upwards by convection displacing existing gases in the air-filled porosity above the plane of the drip lines. In short, the aeration treatments would in effect flush this air-filled porosity. This flushing effect would impact a larger volume of soil with increasing tubing placement depth. Permanent or semi-permanent sub-surface drip irrigation systems need to be placed at depths that permit mechanical surface cultivation. This would reduce the potential of hypoxia. Also, since water and air occupy the same pore space, the air-filled porosity in a given soil volume would increase as water is removed by evapotranspiration. More frequent flushing would increase O_2 available for root metabolic activities and promote root growth.

Increasing levels of aeration frequency would supply more O_2 for plant aerobic respiration and generally this would positively increase growth and yield. Any positive effect of aeration increasing soil ventilation on root growth would translate into improved yield and growth as reflected in the consistently higher values of yield, LAI, and DM with increasing soil aeration frequency. Aeration frequency significantly increased tomato growth performance and fruit yield (Table 4). As expected, increasing aeration frequency progressively increased dry matter and marketable fresh fruit yield of tomato (Figure 4, Figure 6), consistent with previous studies that reported that improving of the soil air condition can increase crop yield [18–21]. This study indicate that aeration largely relieves the hypoxic stress in the root area, high-frequency aeration can significantly increase the plant growth performance. In addition, the aeration treatments tended to significantly impact most responses measured after 25 DAT. Although soil aeration did not significantly affect the LAI_{55} and LAI_{75} , the leaf DM response was significant. The reason for this is most likely due to uncontrollable factors (such as solar angle, cloudiness, etc.) that increase the variability in the measured LAI by the canopy solar radiation transmittance method.

Effect of irrigation on muskmelon growth

The plots were drip-irrigated at 23 and 60 DAT based on the measured gravimetric water content averaged over the 0–60 cm depth of the soil profile on these dates. Based on the volumetric water content of 0.24 measured at transplanting there would be an additional 100 mm $\times$ (0.24 - 0.13) = 11 mm of plant available water in the 50 - 60 cm profile depth. This would imply a total of 136 mm when added with the 125 mm made available in the 0–50 cm from the surface irrigation at the time of transplanting. This stored water would support an evapo-transpiration rate of close to 6 mm per day over the 0 - 23 DAT period. This implies there was very likely no soil water deficits during this period. Any effect of the deficit drip irrigation levels at the different tubing placement depths would therefore be more apparent for responses measured after 25 DAT.

At 23 and 60 DAT the plots were drip irrigated with a volume equivalent to the amount required to replenish the measured soil water storage in the 0–60 cm profile depth to 70, 80, or 90% of field capacity. For the I_{70} treatment, this would imply making plant available water in the soil wetted volume around the emitters equal to $600 \times (0.7 \times 0.38 - 0.13)$ mm = 82 mm for both the 37-day period between 23 and 60 DAT, and for the 15-day period between 60 DAT and harvest at 75 DAT. Corresponding values were 104 mm for I_{80} and 127 mm for I_{90} .

In this study, the emitters were spaced 30 cm along the tubing and the tubing was placed 50 cm apart. The foregoing review indicates that the entire thickness of the soil profile for at most 13 cm above and 13 cm below the plane of the drip line placement depths would be wetted by drip irrigation. This thickness would increase with increasing irrigation level. These literature results relating to a soil with the same texture as that used in this study, along with the non-significant effects of irrigation level on most of the post–25 DAT responses (Table 4), tend to confirm that soil water was not a limiting factor in this experiment. The marketable fruit yield, LAI_{55} , and LAI_{75} remained unaffected by irrigation level (Table 4, Figures 1 and 2). For all the measured dry matter accumulation responses at 75 DAT, only the root DM means for the I_{80} and I_{90} irrigation levels were significantly lower compared to the I_{70} level mean (Table 4 and Figure 2). The irrigation use efficiency for both fruit yield (IUE_f) and total DM accumulation (IUE_{dm}) decreased significantly with increasing irrigation level (Table 4). This would imply that irrigation water applied above the I_{70} level did not contribute to growth and yield since there was no effect of irrigation level on fruit yield and total DM accumulation.

Effect of burial depths of subsurface tubing on muskmelon and tomato growth

Increasing the placement depth for a given irrigation/aeration level would correspondingly change the position of the soil moisture or soil O_2 around the emitter. The shape of the wetted volume is expected to change with depth also in homogenous soils due to the effects of transpiration, evaporation and/or ground water. In addition, in soils with marked changes in physical and hydraulic properties with depth increasing the emitter depth would also induce changes in the shape of the wetted volume. Both muskmelon and tomato are moderate-rooted plant, the roots are mainly distributed within 40 cm of the soil surface. The results showed that muskmelon plant DM increased with increasing tubing placement depth (Figure 2, Table 4). We speculate that lower dry matter accumulation at a shallow depth (10–25 cm) of aeration/ irrigation lines due to the chimney effect. For the root zone soil texture used in this study, the experimental results, in their entirety, tend to support this reasoning. In addition, Wetting the profile 13 cm above and 13 cm below the plane of the drip line placement would imply increasing potential water losses due to soil evaporation for the shallow placement depth with $D_{10} > D_{25} > D_{40}$.

Interactions of soil aeration, burial depths and irrigation on plant growth

Irrigation increases the soil water content surrounding the roots, reducing air-filled porosity. If the roots are confined to the soil volume wetted under subsurface drip irrigation, the possibility of hypoxia in the wetted portion of the root zone under sub-surface drip irrigation is almost certain, especially in heavy soils. On the other hand, different aeration and irrigation depth (position) would result in different soil air and water redistribution. All these interactions will inevitably affect the plant growth.

Until 23 DAT only the soil aeration treatments were applied via the 10, 25, and 40 cm tubing placement depths. Neither irrigation levels or tubing placement depth had any effect on the marginal mean for LAI_{25} . Any effect of these 2 treatment factors would be apparent in the LAI measured at 25 DAT. Nevertheless, the 2-factor D $\times$ A interaction was significant affected LAI_{25} (Table 4). On the other hand, all the soil aeration treatments positively affected LAI_{25} compared to the no aeration treatment. This suggests that low natural soil aeration may be a limiting factor in the clay loam soil used in this study. It confirms that artificial ventilation would positively affect growth, and provides more support for studies showing beneficial effects of this practice as was reported by Bhattarai et al. [10] in his comprehensive review of soil aeration research. According to our studies we found that only the D $\times$ I two-factor interaction was significant affected muskmelon fruit yield (Table 4). This suggests that tubing placement depth determine the position of the soil wetted. The difference of rhizosphere soil moisture results in the plants grow differently. Also, the 2-factor D $\times$ A interaction on LAI_{25} and Root DM were significant indicating that the aeration effect may not be independent of application depth in an initially wet soil profile. On the other hand, the significant 2 factor D $\times$ I and A $\times$ I interactions on IUE_{dm} indicated that the irrigation level effects varied differently for the tubing placement and aeration treatment factors.

The foregoing discussion raises the question as to whether the roots were able to fully access all the plant available water. Also, how could soil aeration influence the IUE and dry matter partitioning? Unfortunately, there are no recent field investigations on the root system development of muskmelon plants and how the roots explore the soil profile. The only available report was the visual investigation of Bruner and Weaver [22] close to a century ago on the root systems of most of the economically important vegetable crops. Assuming a similar overall root architecture and distribution for the Hami melon, it was quite possible that some of the total applied irrigation at the I_{80} and I_{90} may not have been accessible to the plants. If so, this would explain the lack of irrigation effect on the growth responses and the significant decreases in IUE_f and IUE_{dm} with increasing irrigation level (Table 4, Figures 1 to 3).

In general, all management practices to optimize the root environment can only indirectly influence crop growth and yield through their direct effect on the root systems with limits dictated by the species genetics [23]. Muskmelon and tomato plant roots are especially vulnerable to lower oxygen in the soil air [24].

Hypoxia stress may reduce transpiration, restrict nutrient absorption, and inhibit plant growth [25]. Hypoxic conditions have been shown to reduce root weight, length, surface area, and volume of some vegetable crop species [8, 26, 27]. O₂ deficiency in the soil reduces adenosine triphosphate (ATP) production leading to lower uptake and transport of nutrients to the shoot leading to a reduction in leaf growth and photosynthesis [28]. The results of this study on muskmelon add new information to the findings of Bhattarai et al. [11, 29–31] and Sharma et al. [32] that show positive effects of soil aeration on growth and yield of other crops.

Conclusions

The results of this experiment show that it is feasible to configure installation and operation of commercially-available, permanent or semi-permanent, sub-surface drip irrigation systems to manipulate the root environment and indirectly influence growth and yield of greenhouse-produced muskmelon and tomato. For muskmelon experiment, deeper drip tubing placement permits a wider range of mechanical cultivation practices but can induce O₂ deficits in the wetted zone around the emitters especially for low-frequency, high-volume irrigation applications. The fruit yield of muskmelon and tomato increased with increasing aeration frequency, and 1-d aeration intervals was increased the yield of muskmelon by 21.5% compared with the control, and the D₁₅A₂ was increased the tomato yield by 27.8% compared with the D₁₀A_N. Our results demonstrated that the negative impact of any such deficit on the measured responses can be offset by soil aeration via the drip tubing.

Methods

Experimental conditions, setup, and treatments

The muskmelon experiment was conducted in a 108 m long and 8 m wide greenhouse located in Yangling, Shaanxi Province, Northwest China (34°17'N latitude, 108°02'E longitude) from April 24 to July 12, 2014. Tomato experiment was conducted from Oct 18 2014 to May 20, 2015 in the same greenhouse. The climate is semi-arid with a long-term average annual precipitation of 550–650 mm, with the average annual sunshine of 2163.8 hours and 210 frost-free days. The soil texture of root growth area was clay loam with 25.4 % sand, 44.1 % silt, and 30.5% clay. pH was 7.82, dry bulk density 1.34 g cm⁻³, porosity 49.4 %, and gravimetric field capacity 28.2% (volumetric field capacity 38%). The physical and chemical characteristics of the irrigation water: pH was 7.90, EC was 2.71 ds m⁻¹, total suspended solids were 15 mg L⁻¹, COD_{Mn} was 1.2 mg L⁻¹.

The experimental plots consisted of 5.5 m by 0.2 m high flat ridges that were separated by 0.15 m deep furrows. The experimental setup of muskmelon was designed to examine effects on plants under three levels of sub-surface drip irrigation in combination with drip-tubing placed at each of 3 depths in the soil, and 4 levels of artificial soil aeration. The drip irrigation tubing placement depths were 10, 25, and 40 cm below the surface of the ridge designated as D_{cm} (i.e. D₁₀, D₂₅, and D₄₀). The tomato experiment was examining drip irrigation tube burial depth plus aeration frequency. Drip irrigation tubes (φ16 subsurface drip irrigation pipe, Qinchuan water-saving irrigation equipment engineering Co. Ltd, Yangling, China), 16 mm diameter with emitter spacing of 0.30 m, were buried to the appropriate depth spaced 0.50 m apart along the ridges. The subsurface drip irrigation tubes had a peculiar labyrinth channel structure, so it can promote the uniformity discharge rate of air/water as much as possible. The drip irrigation tubes were connected to a distribution system designed to supply both water and air. Each plot had 35 to 36 emitters.

Muskmelon cultivar Shantian No.1 seeds were sown in commercial seedling plugs (Northwest New Horizon Facilities Agriculture Development Co. Ltd, Yangling Shaanxi, China). Shantian No.1 is one of over 100 cultivars of the Chinese 'Hami' reticulated melon group (*Cucumis melo* L.). It is an early maturing, monoecious cultivar with separate male and female flowers on the same plant. Each plant produces 4–5 small (300 - 350 g), fragrant, sweet, crisp-fleshed, fruits that are very popular with consumers. The tested cultivar of tomato (*Lycopersicon esculentum* Mill.) was Fen-Yu-Yang-Gang (Northwest New Horizon Facilities Agriculture Development Co. Ltd, Yangling Shaanxi, China).

After 20 days, 26 plugs of muskmelon (or tomato) were transplanted to the experimental plots spaced 0.40 m apart within 2 rows spaced 0.5 m apart on the ridges. To prevent the lateral spread of air and water into adjacent treatments, the plots were separated from each other by a 1.5 m wide empty space. Post-transplanting management practices (i.e. fertilization, agricultural chemicals spraying, fruit pruning etc.) for all plots were consistent with local production practice. Fruiting was not restricted, although some farmers prune the flowers.

Based on the balance between soil air update rate and labor cost, artificial aeration treatments of tomato were none or aeration at 2-day, and 4-day intervals, and interval of aeration for muskmelon were none or aeration at daily, 2-day, and 4-day intervals beginning the first day after transplanting and designated as A_{interval in day} (i.e. A₁, A₂, A₄, and A_N). For each treatment, 405 L of air was applied to each plot via the drip tubing using a manifold connected to an air compressor. The flow rate for each plot was about 10.2 L min⁻¹. The air which injected via subsurface drip irrigation tubes have a characteristic of high O₂ concentration and low CO₂ concentration compared with air which originally stored in soil pore space. The injected air/oxygen consumed by soil microorganisms, soil animals, crop roots. Moreover, a fraction of oxygen diffuses to the atmosphere because of the chimney effect. This volume was calculated as:

[See supplementary files for formula]

where V_A was the volume of air injected (liter), S the area of a 30-cm deep cross-section between rows (1,500 cm² = 50 cm x 30 cm for 2 rows spaced 50 cm apart), L the plot length (550 cm), p_b the soil dry bulk density of soil (1.35 g cm⁻³), and p_s the soil particle density (2.65g cm⁻³). η = 0.95 an application efficiency coefficient for subsurface drip irrigation.

Irrigation timing and amount demand of tomato experiment is mainly driven by farmers' perceptions and climatic conditions. For the muskmelon experiment, following recommended production practices the plots were surface-irrigated at the time of transplanting. The gravimetric water content (θ_g) averaged over the 0–60 cm at the time of transplanting was measured, and all the plots were surface irrigated with 385 litre (equivalent to 70 mm depth) applied to each plot. Subsequent sub-surface drip irrigation treatment levels, applied at 23 and 60 days after transplanting, were based on the measured gravimetric water content averaged over the 0–60 cm depth of the soil profile on these dates. The location of soil sampling was between two rows of muskmelon (or tomato), each soil sampling with three replicates. Muskmelon treatments, designated as $I_{\text{to\% field capacity}}$ (i.e. I_{70} , I_{80} , and I_{90}), were based on replenishing the water in the soil volume (V_s) in 60 cm of the soil profile ($V_s = 5.5 \text{ m}^2 \times 0.6 \text{ m}$) to 70, 80, and 90 % of the gravimetric field capacity. The irrigation treatment amount in litre of muskmelon were calculated as:

[See supplementary files for formula]

Where V_i was the irrigation amount (liter), b was soil dry bulk density (1350 kg m^{-3}), θ_{gfc} gravimetric water content at field capacity, q_1 the irrigation level (0.7, 0.8, or 0.9), q_2 the measured gravimetric soil moisture content for a given plot, and $\eta = 0.95$ an application efficiency coefficient for subsurface drip irrigation (Pei and Bie, 2008). Irrigation timing demand is mainly driven by farmers' perceptions and climatic conditions. Details of irrigation timing and amounts during muskmelon growth periods are shown in Table 1. Pre-irrigation soil moisture of muskmelon for different treatments and soil depth at 22 and 59 DAT are shown in Table 2.

Experimental design

Muskmelon experimental design

A full factorial [4(levels of aeration frequencies) $\times$ 3 (levels of sub-surface drip irrigation) $\times$ 3 (levels of burial depths)] of 36 experimental treatment combinations would require 108 plots for three replicates. Since there was not enough space to accommodate all these plots, a balanced one-third fractional factorial design [34, 35] was developed using 12 of the 36 treatment combinations. Two $L_9(3^4)$ orthogonal arrays were prepared and superposed. Removing duplicates after superposition yielded the $L_{12}(4 \times 3^2)$ quasi-orthogonal design matrix (Table 3). The treatments were assigned to the experimental plots in a completely randomized layout.

The design is balanced since each level occurs the same number of times for each factor (row). However, every pair of levels occurs the same number of times for factor pairs (A D) and (A I) but not for pair (D I). For the factor pair (D I), there are 9 level pairs but pairs ($D_{10} I_{70}$), ($D_{25} I_{80}$), and ($D_{40} I_{90}$) occurs twice while the remaining 6 level pairs occur once. While not fully orthogonal, the design was as statistically efficient as possible.

A full $4^1 \times 3^2$ factorial of the 36 experimental treatment combinations and would require 108 plots for 3 replicates (Table 3). As with all fractional factorial designs, some effects are not estimable and confounding of lower and higher order effects is unavoidable. In this case, the three-factor interaction effect was not estimable. The main effects are independently estimable and it was possible to determine the existence of two-factor interactions. Even with these limitations, the design provided good stability and permitted estimation of the effects of primary interest comparable to the output of the much more expensive complete factorial experiment requiring 108 experimental plots.

Tomato experimental design

The experiment was limited to 6 treatments arranged as a randomised complete block design with 2 factors (drip irrigation tube burial depth and aeration frequency). The experiment used 2 drip irrigation tube burial depths (D): D_{15} and D_{40} represent drip irrigation tube burial depths of 15 and 40 cm, respectively. The tomato experiment used 3 aeration frequencies (A): A_N , A_2 , and A_4 represent no aeration, aeration once every 2 d, and aeration once every 4 d, respectively. The two experiments resulted in a total of 6 treatments, namely, $D_{15}A_N$, $D_{15}A_2$, $D_{15}A_4$, $D_{40}A_N$, $D_{40}A_2$ and $D_{40}A_4$, each of which was repeated three times.

Plant measurements

At 75 days after transplanting (DAT), all marketable fruits of muskmelon were harvested from each plot. And 214 days after transplanting (DAT), all marketable fruits of tomato (3 trusses) were harvested from each plot. The fruits were weighed and the fresh fruit weight per plant calculated. At 25, 55, and 75 DAT leaf area index (LAI) was measured by using AccuPARLP–80 canopy analyzer (Decagon Devices, Pullman, Washington 99163, USA) based on solar radiation transmittance. After harvesting, the remaining above-ground portion of all plants in each experimental plot were collected. The roots were removed and washed through a sieve. The stem, leaf and root dry weight were dried in the oven at 105 °C for 15 min to deactivate enzymes, and then dried at 75 °C to constant mass before weighing. Root dry weight was then measured on 3 muskmelon (tomato) plants from each plot. A cylinder of soil 0.6 m in diameter and 0.5 m in depth was isolated by digging a circular trench centered around the plant. The cylinder was removed, placed on the 100-mesh steel sieve, soaked, and gently washed to separate the roots from the soil. The plant roots were dried in the oven at 105 °C for 15 min to deactivate enzymes and allowed to dry completely at 75 °C before weighing.

Data analyses and statistics

The experimental data were organized in Microsoft Excel 2016. The statistical analyses were performed with the SPSS 22 software package (IBM, Armonk, New York). All figures were constructed using the graphing software OriginPro 9.0 (Origin Lab Corporation, One Roundhouse Plaza, Suite 303, Northampton, MA 01060, USA).

Muskmelon Data

Data are expressed as the mean. Three replicates were used for each experimental determination. Data were analyzed using a residual test method before statistical analysis, and the data met the assumption of homogeneity of variances and followed normal distribution. Mean differences between treatments were assessed by analysis of variance (ANOVA). *Post-hoc* pairwise comparisons of the treatment means were performed using Duncan's multiple range test. Differences were considered significant at the level of 0.05. The main purpose of the ANOVA was to assess the main effects and the 2-way interactions between drip irrigation tube burial depth, irrigation level and artificial aeration frequency on tomato yield, LAI, post-harvest dry matter partitioning, and irrigation use efficiency. The significances were defined at the level of 0.05 and 0.01.

Tomato Data

The experimental design was taken as a 2 x 3 factorial with 3 replicates. Data were analyzed using a residual test method before statistical analysis, and the data met the assumption of homogeneity of variances and followed normal distribution. Multiple comparisons using Duncan's new multiple-range test were completed whenever the ANOVA indicated significant differences at the level of 0.05.

Declarations

Abbreviations

EC: Electrical conductivity; DAT: Days after transplanting; LAI: leaf area index; DM: dry matter; D_{cm} (i.e. D_{10} , D_{25} , and D_{40}): Irrigation tubing placement depths were 10, 25, and 40 cm below the surface of the ridge; IUE_f or IUE_{dm} : Irrigation use efficiency as (marketable fresh fruit yield per plant) or as (g total DM per plant) divided by (liter total irrigation water applied); $A_{interval\ in\ day}$ (i.e. A_1 , A_2 , A_4 , and A_N): Interval of aeration for muskmelon/tomato were none or aeration at daily, 2-day, and 4-day intervals beginning the first day after transplanting; $I_{to\% \text{ field capacity}}$ (i.e. I_{70} , I_{80} , and I_{90}): Muskmelon treatments, designated as, were based on replenishing the water in the soil volume (V_s) in 60 cm of the soil profile ($V_s = 5.5\ m^2 \times 0.6\ m$) to 70, 80, and 90 % of the gravimetric field capacity; LAI_{days} (i.e. LAI_{25} , LAI_{55} , and LAI_{75}): LAI of muskmelon plants measured by canopy solar radiation transmittance at 25, 55, and 75 days after transplanting.

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Availability of data and materials

The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

competing interests

The authors declare that they have no competing interests

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Authors' contributions

Conceived and designed the experiments: LY and NWQ. Performed the experiments: LY and ZMZ. Analyzed the data: LY and WJW. Contributed reagents/materials/analysis tools: LY CXS WJW ZMZ ZZX. Wrote the paper: LY. Revised the manuscript: LY, NWQ, CXS and ZZX. All authors have read and

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References

1. Ben-Noah I, Friedman SP. Review and evaluation of root respiration and of natural and agricultural processes of soil aeration. *Vadose Zone J.* 2018; 17: 170119.
2. Smit B, Stachowiak M, Volkenburgh V. Cellular processes limiting leaf growth in plants under hypoxic root stress. *J Exp Bot.* 1989; 40: 89–94.
3. Li TL, Chen YD, Liu YL, Qin X. Effects of rhizosphere CO₂ concentration on root growth and activity of netted muskmelon. *Transactions of the CSAE.* 2009; 25: 210–215.
4. Liu YL, Li TL, Sun ZP, Chen YD. Effects of Rhizosphere CO₂ Concentration on Plant Growth and Root Nitrogen Metabolism of Muskmelon. *Scientia Agricultura Sinica.* 2010; 43: 2315–2324.
5. Liu YL, Li TL, Sun ZP, Chen YD. Impacts of root-zone hypoxia stress on muskmelon growth, its root respiratory metabolism, and anti oxidative enzyme activities. *Chinese Journal of Applied Ecology.* 2010; 21: 1439–1445.
6. Bhattarai SP, Dhungel J, Midmore DJ. Oxygation improves yield and quality and minimizes internal fruit crack of cucurbits on a heavy clay soil in the semi-arid tropics. *Journal of Agricultural Science.* 2010; 2: 17–25.
7. Chen XM, Dhungel J, Bhattarai SP, Torabi M, Pendergast L, Midmore DJ. Impact of oxygation on soil respiration, yield and water use efficiency of three crop species. *J Plant Ecol.* 2011; 4: 236–248.
8. Pendergast L, Bhattarai SP, Midmore DJ. Benefits of oxygation of subsurface drip-irrigation water for cotton in a vertisol. *Crop Pasture Sci.* 2013; 64: 1171–1181.
9. Bhattarai SP, Huber S, Midmore DJ. Aerated subsurface irrigation water gives growth and yield benefits to Zucchini, vegetable soybean and cotton in heavy clay soils. *Ann Appl Biol.* 2004; 144: 285–298.
10. Bhattarai SP, Midmore DJ. Influence of soil moisture on yield and quality of tomato on a heavy clay soil. *Proceedings of the International Symposium on Harnessing the Potential of Horticulture in the Asian-Pacific Region.* 2005; 451–454.
11. Bhattarai SP, Pendergast L, Midmore DJ. Root aeration improves yield and water use efficiency of tomato in heavy clay and saline soils. *Sci Hortic.* 2006; 108: 278–288.
12. Bhattarai SP, Midmore DJ, Pendergast L. Yield, water-use efficiencies and root distribution of soybean, chickpea and pumpkin under different subsurface drip irrigation depths and oxygation treatments in vertisols. *Irrig Sci.* 2008; 26: 439–450.
13. Zhu LF, Yu SM, Jin QY. Effects of aerated irrigation on leaf senescence at late growth stage and grain yield of rice. *Rice Science.* 2012; 19: 44–48.
14. Rieu M, Sposito G. Fractal Fragmentation, Soil Porosity, and Soil Water Properties: I. Theory. *Soil Sci Soc Am J.* 1991; 55: 1231–1238.
15. Biemelt S, Keetman U, Albrecht G. Re-aeration following hypoxia or anoxia leads to activation of the antioxidative defense system in roots of wheat seedlings. *Plant Physiol.* 1998; 116: 651–658.
16. Drew MC. Oxygen deficiency and root metabolism: injury and acclimation under hypoxia and anoxia. *Annu. Rev. Plant. Physiol. Plant Mol. Biol.* 1997; 48: 223–250.
17. Munns R, Sharp RE. Involvement of abscisic acid in controlling plant growth in soils of low water potential. *Aust J Plant Physiol.* 1993; 20: 425–437.
18. Bonachela S, Quesada J, Acuna RA, Magan JJ, Marfa O. Oxyfertigation of a greenhouse tomato crop grown on rockwool slabs and irrigated with treated wastewater: Oxygen content dynamics and crop response. *Agric Water Manage.* 2010; 97: 433–438.
19. Ityel E, Ben-Gal A, Silberbush M, Lazarovitch N. Increased root zone oxygen by a capillary barrier is beneficial to bell pepper irrigated with brackish water in an arid region. *Agric Water Manage.* 2014; 131: 108–114.
20. Shahien MM, Abuarab ME, Magdy E. Root aeration improves yield and water use efficiency of irrigated potato in sandy clay loam soil. *Int J Adv Res.* 2014; 2(10): 310–320.
21. Li Y, Niu WQ, Wang JW, Liu L, Zhang MZ. Effects of artificial soil aeration volume and frequency on soil enzyme activity and microbial abundance when cultivating greenhouse tomatoes. *Soil Sci Soc Am J.* 2016; 80: 1208–1221.

22. Bruner WE, Weaver JE. Muskmelon In: Root development of vegetable crops. McGraw-Hill Book Company: New York. 1927
23. Boyer JS. Plant Productivity and Environment. Science. 1982; 218: 443–448.
24. Gao HB, Jia YX, Guo SR, Lv GY, Wang T, Juan L. Exogenous calcium affects nitrogen metabolism in root-zone hypoxia-stressed muskmelon roots and enhances short-term hypoxia tolerance. J Plant Physiol. 2011; 168: 1217–1225.
25. Morard P, Silvestre J. Plant injury due to oxygen deficiency in the root environment of soilless culture: A review. Plant Soil. 1996; 184: 243–254.
26. Liang J, Zhang J, Wong MH. Effects of air-filled soil porosity and aeration on the initiation and growth of secondary roots of maize. Plant Soil. 1996; 186: 245–254.
27. Xu CM, Wang DY, Chen S, Chen LP, Zhang XF. Effects of Aeration on Root Physiology and Nitrogen Metabolism in Rice. Rice Science. 2013; 20: 148–153.
28. Barrett-Lennard EG. The interaction between waterlogging and salinity in higher plants: causes, consequences and implications. Plant Soil. 2003; 253: 35–54.
29. Bhattarai SP, Midmore DJ. Oxygenation of rhizosphere with subsurface aerated irrigation water improves lint yield and performance of cotton on saline heavy clay soil. In: 4th International Crop Science Congress. Brisbane, Australia; 2004.
30. Bhattarai SP, Su N, Midmore DJ. Oxygenation unlocks yield potentials of crops in oxygen-limited soil environments. Adv Agron. 2005; 88: 313–377.
31. Bhattarai SP, Salvaudon C, Midmore DJ. Oxygenation of the Rockwool Substrate for Hydroponics. Aquaponics Journal. 2008, 49:29–33.
32. Sharma SP, Leskovar DI, Crosby KM, Volder A, Ibrahim AMH. Root growth, yield, and fruit quality responses of reticulatus and inodorus melons (*Cucumis melo* L.) to deficit subsurface drip irrigation. Agr Water Manage. 2014; 136: 75–85.
33. Niu WQ, Fan WT, Persaud N, Zhou XB. Effect of post-irrigation aeration on growth and quality of greenhouse cucumber. Pedosphere, 2013; 23: 790–798.
34. Wu CF, Hamada M. Experiments: Planning, analysis, and parameter design optimization. John Wiley: New York. 2000
35. Collins LM, Dziak JJ, Li R. Design of experiments with multiple independent variables: A resource management perspective on complete and reduced factorial designs. Psychological Methods. 2009; 14: 202–224.

Tables

Table 1. Details of irrigation timing and amounts during muskmelon growth period

Combination	Irrigation timing			Total Irrigation amount (mm)
	0DAT (mm)	23DAT (mm)	60DAT (mm)	
D ₁₀ A _N I ₇₀	70	29.98	53.28	153.26
D ₁₀ A ₁ I ₈₀	70	62.21	70.88	203.08
D ₁₀ A ₂ I ₉₀	70	84.87	94.29	249.16
D ₁₀ A ₄ I ₇₀	70	47.36	59.07	176.43
D ₂₅ A _N I ₈₀	70	57.33	58.47	185.80
D ₂₅ A ₁ I ₉₀	70	88.39	77.01	235.41
D ₂₅ A ₂ I ₇₀	70	49.95	37.82	157.77
D ₂₅ A ₄ I ₈₀	70	64.03	63.11	197.14
D ₄₀ A _N I ₉₀	70	82.75	83.00	235.75
D ₄₀ A ₁ I ₇₀	70	44.20	27.65	141.86
D ₄₀ A ₂ I ₈₀	70	60.88	68.76	199.64
D ₄₀ A ₄ I ₉₀	70	93.67	82.16	245.83

DAT: days after transplanting

Table 2a. Soil moisture for different treatments and soil depth at 22 days after transplanting

Soil depth (cm)	D ₁₀ A _N I ₇₀	D ₁₀ A ₁ I ₈₀	D ₁₀ A ₂ I ₉₀	D ₁₀ A ₄ I ₇₀	D ₂₅ A _N I ₈₀	D ₂₅ A ₁ I ₉₀	D ₂₅ A ₂ I ₇₀	D ₂₅ A ₄ I ₈₀	D ₄₀ A _N I ₉₀	D ₄₀ A ₁ I ₇₀	D ₄₀ A ₂ I ₈₀	D ₄₀ A ₄ I ₉₀
0-10 (% Gra)	17.08	13.54	13.48	10.44	15.48	14.12	9.28	12.99	15.75	11.33	10.24	11.14
10-20 (% Gra)	16.86	16.43	16.61	15.38	16.28	17.20	15.96	16.45	16.82	15.94	16.61	15.84
20-30 (% Gra)	17.31	16.77	16.24	15.73	15.17	17.12	15.15	16.65	16.31	15.82	18.43	15.28
30-40 (% Gra)	16.08	16.57	16.84	15.74	15.89	12.29	15.09	14.12	16.03	16.14	16.17	14.87
40-50 (% Gra)	16.65	15.88	16.95	15.88	17.44	16.82	15.66	16.15	16.50	15.47	19.16	15.87
50-60 (% Gra)	16.37	15.80	16.25	14.94	17.63	16.34	15.13	17.35	16.46	15.62	15.31	17.17
Average (% Gra)	16.72	15.83	16.06	14.68	16.40	15.65	14.38	15.62	16.31	15.05	15.99	15.03

Table 2b. Soil moisture for different treatments and soil depth at 59 days after transplanting

Soil depth (cm)	D ₁₀ A _N I ₇₀	D ₁₀ A ₁ I ₈₀	D ₁₀ A ₂ I ₉₀	D ₁₀ A ₄ I ₇₀	D ₂₅ A _N I ₈₀	D ₂₅ A ₁ I ₉₀	D ₂₅ A ₂ I ₇₀	D ₂₅ A ₄ I ₈₀	D ₄₀ A _N I ₉₀	D ₄₀ A ₁ I ₇₀	D ₄₀ A ₂ I ₈₀	D ₄₀ A ₄ I ₉₀
0-10 (% Gra)	13.06	13.24	17.08	13.91	17.10	16.33	15.79	18.28	17.80	18.71	16.05	17.02
10-20 (% Gra)	14.95	15.63	14.79	14.33	16.89	17.02	15.69	16.45	15.66	16.42	15.35	16.59
20-30 (% Gra)	14.66	15.49	14.99	12.49	15.79	15.97	15.63	16.64	16.70	16.90	14.96	16.82
30-40 (% Gra)	14.08	16.02	14.34	13.53	16.59	20.96	21.08	15.24	16.02	16.95	15.06	15.94
40-50 (% Gra)	13.26	15.28	14.53	13.80	15.58	15.78	14.92	16.16	15.72	17.83	14.49	15.96
50-60 (% Gra)	13.93	13.88	13.99	11.79	15.66	15.79	11.71	11.58	15.79	16.77	14.46	15.96
Average (% Gra)	13.99	12.79	14.95	13.31	16.27	15.83	15.80	15.72	16.28	16.69	15.06	16.38

Table 3. The transposed design matrix for the 12 treatment combinations

Combination	1	2	3	4	5	6	7	8	9	10	11	12
Depth (D)	D ₁₀	D ₁₀	D ₁₀	D ₁₀	D ₂₅	D ₂₅	D ₂₅	D ₂₅	D ₄₀	D ₄₀	D ₄₀	D ₄₀
Aeration (A)	A _N	A ₁	A ₂	A ₄	A _N	A ₁	A ₂	A ₄	A _N	A ₁	A ₂	A ₄
Irrigation (I)	I ₇₀	I ₈₀	I ₉₀	I ₇₀	I ₈₀	I ₉₀	I ₇₀	I ₈₀	I ₉₀	I ₇₀	I ₈₀	I ₉₀

Table 4. Marginal means and 2-factor interactions for marketable fruit yield, LAI, post-harvest dry matter partitioning, and irrigation use efficiency response of greenhouse-produced muskmelon plants to sub-surface drip-irrigation tubing placement depth x soil aeration frequency x irrigation level treatment factors. In each row, the means for the levels of a given factor not followed by the same letter are significantly different at the 5% level. Two-factor interaction is significant at the 1 % (**), 5% (*), or not significant (ns) level

Response	Tubing Placement Depth (D _{cm})			Soil Aeration Frequency (A _{interval in day})				Irrigation Level (I _{to % field capacity})			F-value					
	D ₁₀	D ₂₅	D ₄₀	A ₁	A ₂	A ₄	A _N	I ₇₀	I ₈₀	I ₉₀	D	A	I	DxA	DxI	AxI
Yield (kg)	1.48ab	1.59a	1.38b	1.64a	1.51ab	1.43b	1.35b	1.53a	1.51a	1.40a	3.012ns	1.995ns	0.753ns	0.296ns	3.606*	0.988ns
LAI ₂₅	1.41a	1.41a	1.11a	1.63a	1.42a	1.33a	0.84b	1.38a	1.41a	1.13a	1.128ns	8.087**	1.608ns	3.018*	1.143ns	2.674ns
LAI ₅₅	2.22b	3.05a	2.81a	3.11a	2.55a	2.62a	2.48a	2.52a	2.61a	2.94a	5.334**	1.028ns	2.029ns	1.486ns	1.792ns	1.623ns
LAI ₇₅	2.31b	3.25a	3.02a	3.00a	3.06a	2.96a	2.43a	2.63a	3.02a	2.94a	5.788**	1.201ns	0.777ns	1.017ns	0.986ns	2.703*
Total DM (g)	43.3b	52.9ab	60.3a	62.6a	54.2ab	49.2b	42.6b	52.2a	51.6a	52.6a	5.347**	3.900*	0.017ns	0.440ns	3.821*	2.659*
Stem DM (g)	11.3b	11.1b	13.2a	13.6a	12.2ab	11.4bc	10.3c	12.1a	11.9a	11.6a	4.325*	5.880**	0.158ns	2.450ns	7.550**	5.376**
Leaf DM(g)	29.9b	40.1a	44.9a	46.4a	39.9ab	36.0ab	30.9b	37.8a	37.9a	39.2a	5.109*	2.589ns	0.041ns	0.294ns	2.469ns	2.062ns
Root DM (g)	2.01a	1.79a	2.14a	2.52a	2.07b	1.88bc	1.47c	2.31a	1.82b	1.82b	1.187ns	8.887**	3.337*	4.014**	8.847**	2.320ns
IUE _f (g liter ⁻¹)	17.0a	18.8a	15.8a	20.0a	17.4a	15.1a	16.3a	21.5a	17.2b	12.9c	0.986ns	1.450ns	14.198**	1.623ns	2.677ns	6.178**
IUE _{dm} (g liter ⁻¹)	6.15b	7.64ab	8.94a	9.75a	7.81ab	6.53b	6.20b	9.23a	7.29b	6.20b	2.827ns	2.971*	3.524*	4.388**	5.694**	3.996**

Yield is kg per plant for all marketable fruits harvested at 75 day after transplanting (DAT); LAI = Leaf area index measured by canopy solar radiation transmittance method; LAI_{xx} = LAI measured at xx DAT; DM = g per plant dry matter at 75 DAT; IUE_f or IUE_{dm} = irrigation use efficiency as (marketable fresh fruit yield per plant) or as (g total DM per plant) divided by (liter total irrigation water applied)

Figures

Figure 1

LAI of muskmelon plants measured by canopy solar radiation transmittance at 25, 55, and 75 days after transplanting for each combination of drip-tubing placement depth, soil aeration frequency, and irrigation level treatment factors. Combination treatment means are annotated along polar axis. Duncan 0.05 for mean comparison at 25, 55, and 75 DAT were 0.50, 1.16, and 1.12.

Figure 2

Post-harvest stem, leaf, and root dry matter of muskmelon plants measured at 75 days after transplanting for each combination of drip-tubing placement depth, soil aeration frequency, and irrigation level treatment factors. Bars on the stacked sections for each component represent the standard error of the mean. Means not followed by the same letter are significantly different at the 5% level.

Figure 3

Ternary plot of root, stem, and leaf dry weight of muskmelon expressed as % of total post-harvest plant dry weight measured at 75 days after transplanting for each combination of drip tubing placement depth, soil aeration frequency, and irrigation level treatment factors.

Figure 4
 Post-harvest stem, leaf, and root dry matter of tomato measured for each combination of tubing placement depth (Dcm) and aeration frequency(A interval in day) treatment factors. The differences were compared using the Duncan's test with a significance level of 0.05.

Figure 5

Marketable fruit yield of muskmelon measured for each combination of tubing placement depth (Dcm), aeration frequency (A interval in day), and irrigation level (I to% field capacity) treatment factors. Duncan0.05 for combination treatment mean comparison = 0.40 kg

Figure 6

Fruit yield of tomato for each combination of tubing placement depth (Dcm) and aeration frequency (A interval in day) treatment factors. The differences were compared using the Duncan's test with a significance level of 0.05.

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- [MethodsFormulas.docx](#)