



Research article

Effects of stem training on the physiology, growth, and yield responses of indeterminate tomato (*Solanum lycopersicum*) plants grown in protected cultivationMlungisi F. Mngoma^a, Lembe S. Magwaza^{a,b,*}, Nkanyiso J. Sithole^{c,d,**}, Shirly T. Magwaza^e, Asanda Mditshwa^a, Samson Z. Tesfay^a, Khayelihle Ncama^{c,d}^a Discipline of Horticultural Science, School of Agricultural, Earth and Environmental Sciences, University of KwaZulu-Natal, Private Bag X01, Scottsville, 3209, Pietermaritzburg, South Africa^b Discipline of Crop Science, School of Agricultural, Earth and Environmental Sciences, University of KwaZulu-Natal, Private Bag X01, Scottsville, 3209, Pietermaritzburg, South Africa^c Department of Crop Sciences, Faculty of Natural and Agricultural Sciences, North-West University, Private Bag X2046, Mmabatho, 2790, South Africa^d Food Security and Safety Niche Area, Faculty of Natural Sciences, North-West University, Mmabatho, 2790, South Africa^e Department of Agricultural Science, University of Zululand, Private Bag X1001, KwaDlangezwa, 3886, South Africa

ARTICLE INFO

Keywords:

Stem training
Gas exchange
Indeterminate tomatoes
Growth
Yield

ABSTRACT

The lower yield of tomatoes grown in tunnels, due to the limited space, remains a challenge. Stem training has long been identified as one of the most important horticultural practices used to improve the yield and fruit quality of tomatoes grown in commercial tunnels; however, there is little information available on the dome-shaped tunnels that are used, particularly by smallholder farmers. The common stem-training methods used in tunnels include the Single-Stem (SS), the Double-Stem (DS) and the Two-Plants-per-Pot (TPP) methods. Their effect on the plants' growth, development and physiology varies significantly, and hence, it affects crop productivity. The experiment was conducted in an 8 m × 30 m dome-shaped tunnel and the treatment included the single-stem, double-stem and two-plants-per-pot methods. A higher photosynthetic rate was observed in the SS treatment, followed by the DS treatment. Similar trends were found in the growth, yield and fruit quality parameters of the SS and DS treatments. However, the DS and TPP treatments exhibited, on average, a higher number of fruits, as well as a higher colour index, TSS, TA and Brima per harvest, than the SS treatment. The study indicated that the double-stem and two-plants-per-pot training methods are the best for farmers who seek to optimize their yields and maximize their profits for this cultivar.

1. Introduction

The production of tomatoes (*Solanum lycopersicum*) under protected cultivation has gained popularity in South Africa over the past decade (Maboko et al., 2011). This increase has been intensified by the high market returns, even in areas with limited resources, such as poor soils and a shortage of land. Producing high yields and crops of good quality in an open field is very challenging, due to unfavourable environmental conditions and the high incidence of pests and diseases. However, planting tomatoes under protected cultivation provides a certain degree of control and allows farmers to produce good crops, even out of season, because it is easier to control the temperature under such systems.

Despite the widespread adoption of protected cultivation, the use of such systems remains a challenge among smallholder farmers who use dome-shaped tunnels with a limited height (they are available at a maximum height of 2–3 m), especially when growing indeterminate tomato cultivars (Alam et al., 2016). The yield of tomatoes grown under protected cultivation does not always reach its full production potential, due to poor management, which is caused by the highly-intensive nature of these systems. Accordingly, several management practices have been developed that aim to improve the yield by enhancing the fruit number, the fruit size and the quality of the fruit (Maboko and du Plooy 2008). These horticultural practices include fruit thinning, the management of the plant population, cultivar selection and stem training (Maboko and

* Corresponding author.

** Corresponding author.

E-mail addresses: magwazal@ukzn.ac.za (L.S. Magwaza), nkanyisoj@gmail.com (N.J. Sithole).<https://doi.org/10.1016/j.heliyon.2022.e09343>

Received 10 January 2022; Received in revised form 27 February 2022; Accepted 25 April 2022

2405-8440/© 2022 The Author(s). Published by Elsevier Ltd. This is an open access article under the CC BY-NC-ND license (<http://creativecommons.org/licenses/by-nc-nd/4.0/>).

du Plooy 2008). Stem training has been identified as one of the most important horticultural practices that is used to increase the yield and improve the fruit quality (Ara et al., 2007). It is defined as “the number of stems that are allowed to grow as leaders during plant growth.” Different stem-training methods are used for tomato production in tunnels and they include single-stem, two-plants-per-pot and double-stem training. Single-stem training is achieved by removing all the sucker stems, in order to allow the plant to grow as a single leader. The two-plants-per-pot stem-training method is achieved by planting two seedlings in one pot, and removing all the sucker stems allows each seedling to grow as a single stem. On the other hand, double-stem training is achieved by leaving a sucker at the bottom to grow as the second main stem, which results in the growth of a double leader stem. Stem-training methods have different effects on both the plant physiology and the yield. Different stem training methods may exhibit a different leaf area index, and percentage of leaves that are exposed to sunlight. In addition, stem training also impacts the root density of tomato plants; for example, the two-plants-per-pot method forms root balls at a later stage and also reduces light interception, which leads to the down-regulation of the photosynthetic capacity (Shi et al., 2008). Furthermore, the stem-training method may also impact numerous other variables, such as the plant's water use efficiency, transpiration and fruit formation.

The most commonly-used stem-training method for the production of indeterminate tomatoes in South Africa is the single-stem method (Snyder 2007). It has been reported that the tomato fruit produced by using this training method are not only large, but have a high fruit mass (Snyder 2007). However, these tomatoes have been reported to have a low marketable fruit and are very susceptible to fruit cracking (Maboko and du Plooy 2009). Furthermore, this training method produces a minimal number of fruit per plant and the fruit are large, which might be the main cause of fruit cracking, thus resulting in a reduction in their marketability (Maboko et al., 2011). Most farmers are trying to optimize their yield by shifting from the single-stem method to the two-plants-per-pot method. Amundson et al. (2012) reported that this method results in a slight increase in yield per unit area and has no impact on the farmers' profits. This steadiness in the profit margin is hypothesized to be related to the additional costs that are incurred when increasing the number of seedlings. These include inputs such as the seedling, fertigation, maintenance and labour costs.

Growing tomatoes with a double stem has been identified as an alternative method that can increase the yield and reduce the production cost compared to the two-plants-per-pot method, because the maintenance costs are similar (Amundson et al., 2012). Alam et al. (2016) found that the BARI hybrid tomatoes produced with a double stem had a high fruit mass, compared to those produced with a single stem. Maboko et al. (2011) reported that the yield of FA593 tomatoes produced by using the double-stem method was higher and the amount of marketable fruit was greater, compared to those using the single-stem method. Similarly, Amundson et al. (2012) found that the two-plants-per-pot method had a high yield of tomatoes during the summer, compared to the double-stem method, whereas there was no significant difference during the winter. The findings reported by these authors necessitate more research, since there is no clear information, or consensus, on the yield of two-plants-per-pot stem training, compared to double-stem training. Thus, this study aims to identify the best stem-training method for increasing the yield and improving the quality of the STAR 9037 cultivar, which is the most widely-grown cultivar in high tunnel commercial production, while at the same time providing information on the horticultural performance of these training methods.

2. Materials and methods

2.1. Experimental treatments

The study was conducted at the University of KwaZulu-Natal's controlled environmental facility in an 8 m × 30 m dome-shaped tunnel,

with a maximum height of 3 m (from the floor to the trellis wire) in a structure covered with polyethylene plastic, during the summer months, between November 2018 and April 2019. The temperature and relative humidity in the tunnel during this period were at an average of 38 °C and 41%, respectively. Six-week-old seedlings of the STAR 9037 cultivar (Starke Ayres Seeds®) were sourced from a local seed company (Sunshine Seedlings®, Pietermaritzburg, South Africa) and were transplanted into 8 L bags filled with fine pine sawdust as the growing medium.

The experiment was arranged as a randomized complete design consisting of stem training methods at three levels. These were the single-stem, the double-stem and the two-plants-per-pot training methods and they were replicated three times, with each replication consisting of four plants, thus resulting in 36 experimental units (3 × 3 × 4). The Single-Stem (SS) training method was achieved by planting one seedling in a pot and removing all the sucker stems as the plant grew, to allow it to grow as a single leader. On the other hand, the Two-Plants-per-Pot (TPP) method was achieved by planting two seedlings in one pot and removing all sucker stems, to allow each seedling to grow as a single stem. The Double-Stem (DS) method was achieved by planting one seedling in a pot and allowing the sucker at the bottom to grow as the second main stem, which resulted in the growth of double leader stems.

A water-soluble inorganic fertilizer mix (commercial fertilizer) in the form of Solucal® (calcium nitrate), Multi-K® (potassium nitrate) and Hygroponic® (ammonium nitrate with all the essential micronutrients and macronutrients) was dissolved in one tank filled with 5000 L of water. The fertilizers were mixed according to the recommended rate for tunnel production by the manufacturer (Hygrotech SA, Pietermaritzburg, South Africa). 2.7 kg Solucal®, 500 g Multi-K® and 3 kg Hygroponic® were mixed with water in a 5000 L tank, from the transplant stage to the third flower stage. At the end of the third flower truss, the fertilizers were increased by mixing 5000 L of water with 3.5 kg Solucal®, 1 kg Multi-K® and 5 kg Hygroponic®. The plants were fertigated by pumping the fertilizer mix into an open-loop fertigation system. Each plant was fertigated for five minutes with a soluble fertilizer mix, by using a dripper that emitted 2 L of dissolved fertilizer per hour. The plants were fertigated at two-hour intervals, from 7:00 am to 1:00 pm; thereafter, they were fertigated hourly until 4:00 pm.

2.2. Gaseous exchange

The leaf gas exchange was measured in Weeks 3, 10, 12, 14 and 18 after planting, by using the Portable Photosynthesis System LI-6400 XT (Licor Bioscience, Inc. Lincoln, Nebraska, USA), which is fitted with an infrared gas analyzer that is connected to a Leaf Chamber Fluorimeter (LCF) (6400-40B, 2 cm² leaf area, Licor Bioscience, Inc. Lincoln, Nebraska, USA). The artificial saturated Photosynthetic Active Radiation (PAR) and external CO₂ were fixed at 1000 μmol m⁻² s⁻¹ and 400 μmol mol⁻¹, respectively. The measurements were taken at 2-week intervals on sunny days, between 11h00 and 13h00. A sample was taken from the apex of one leaf of each plant, which represented the replicate, and it was measured on the same leaf until the termination of study. The gaseous exchange parameters of the leaf, such as the photosynthetic rate (*A*), the stomatal conductance (*g_s*), the transpiration rate (*T*), the intercellular CO₂ concentration (*C_i*) and the ratio of intercellular and atmospheric CO₂ (*C_i/C_a*) concentration were measured. The stomatal limitation was calculated as 1-*C_i/C_a* (Dong et al., 2016), while the Water Use Efficiency (*WUE*) was calculated as the ratio of *A* and *T* (Mashilo et al., 2017).

2.3. Plant growth parameters and yield

The plant height was measured at two-weekly intervals by using a measuring tape. Measurements were taken from the base up to the apical point of the plant. Samples were taken from each plant, which represented the replicates of all the treatments. The stem diameter was measured by using a caliper. Measurements were taken at the base of the stem of each plant, which represented the replicate. The yield of

tomatoes was determined by the number of the fruit harvested and their mass was measured. Fruit sampling for yield and quality measurement was taken on three sampling dates, which were denoted as Harvests 1, 2 and 3. The harvests were conducted at the plant age of 70, 72 and 74 days, respectively. The number of the fruit was determined by counting. On the other hand, the fruit mass was determined by weighing the fruit individually, using a calibrated benchtop balanced weighing scale (WTB200, RADWAG, Poland). The sum of all the fruit harvested and their mass was used to estimate the total yield.

2.4. Total soluble solids (TSS) and titratable acid (TA)

The TSS was measured by using a benchtop digital refractometer (RFM 340 +, Bellingham + Stanley Ltd, UK), based on a method described by Ncama et al. (2017). The juice was obtained by crushing the fruit with a Warring blender and then squeezing the fruit juice into a 50 mL beaker, using a nylon filter. The refractometer was calibrated by cleaning a prism with distilled water, followed by wiping it with a clean paper towel and measuring a zero sample. After calibration, the tomato juice of each fruit, representing a replicate, was measured to determine the TSS.

The TA was measured by using a Mettler Toledo compact titrator G10S. Briefly, samples were prepared by pipetting 8 mL of juice into a 100 mL beaker. Using another clean pipette tip, 42 mL of distilled water were added to the juice in the beaker and titrated with 0.1M NaOH to a pH value of 8.1, by using the Mettler Toledo. The acid was calculated as a percentage of the citric acid, using a factor 0.0064, as in Eq. (1).

$$\text{Percentage acid} = \frac{\text{titre (mlNaOH)} \times \text{ACIDfactor} \times 100}{8(\text{mljuice})} \quad (1)$$

The TA was measured in each fruit per plant, per replicate and per treatment, and the average means of the replicates were taken.

BrimA (Brix minus Acid) is an index that measures the balance between the sweetness and acidity. It was calculated by using Eq. (2), as suggested by Jordan et al. (2001).

$$\text{BrimA} = \text{TSS} - k(\text{TA}) \quad (2)$$

where k is a constant that reflects the least sensitivity of the tongue to the TSS, compared to the TA. The k constant allows the TSS amounts higher than TA to make the same numerical changes to *BrimA*. The equation for *BrimA* (Eq. 2) was adjusted, as recommended by Obenland et al. (2009), who had replaced the constant (k) value of 5 with 3 and 4 (as suggested by Jordan et al., 2001), in order to eliminate the generation of negative *BrimA* values for oranges.

2.5. Fruit colour

The colour of the tomato fruit was measured by using a Konica Minolta Chroma meter CR-300, INC, Japan (Lopez Camelo and Gómez, 2004). Measurements were taken in the equatorial region of the fruit. The fruit samples were scanned in three parts and readings were taken on the chromameter. The colour co-ordinate readings recorded lightness (L^*), green to red (a^*), blue to yellow (b^*), as well as Chroma (C), and the results were combined as the Tomato Colour Index (Hobson et al., 1983) by using Eq. (3).

$$\text{Colour index} = 2000a \div LC \quad (3)$$

2.6. Statistical analysis

The collected data of the measured variables were subjected to an Analysis of Variance (ANOVA) test, using the statistical software GenStat (GenStat1, 18.1 Edition, VSN International, UK). The means were separated by using Fisher's Least Significant Difference (LSD) at a 5% level of significance. The values of Standard Error were calculated where a

significant standard deviation was found at ($p < 0.05$) between the individual values. A Pearson's correlation analysis was performed to describe the pattern of the relationship between the plant growth and leaf gas exchange parameters, by using Microsoft Excel 2010, where calculations were done for both the growth and photosynthesis parameters in Week 12.

3. Results

3.1. Leaf gas exchange in response to different stem-training methods

No differences ($p > 0.05$) were found in the leaf photosynthetic rate (A) of all stem training methods, except for Week 12, where the SS exhibited a higher A ($49.56 \mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-2}$) than the DS ($36.34 \mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-2}$) and the TPP ($39.53 \mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-2}$) training methods (Table 1). Generally, A showed an increased performance during Week 3 until Week 10, and then it declined until the end of the evaluation (Figure 1A).

The interaction between the stem training methods was also significantly different ($p < 0.05$) in A , with the highest value being recorded by a single-stem training method at 12 weeks after transplanting. The different stem training methods exhibited no significant differences ($p > 0.05$) in C_i , C_i/C_a , $1-C_i/C_a$, T and WUE . However, the C_i , C_i/C_a and $1-C_i/C_a$ varied significantly ($p < 0.01$) in relation to the time and interaction of the stem training.

3.2. Plant growth parameters and yield responses to different stem-training methods

Significant differences ($p < 0.05$) were observed among the tested growth and yield parameters, which indicated that there were variable responses of the tomato plants that used different stem training methods. Single-stem training method plants showed an increased plant height, compared to the double-stem and two-plants-per-pot training methods (Figure 2A). The interactions between the training method and time were also significantly different, with single-stem training showing an average mean of 126 cm, compared to the double-stem and two-plants-per-pot training methods (114 cm and 114 cm, respectively.) The highest plant height was observed in Week 12 in all the treatments. Significant differences ($p < 0.05$) were observed in the stem diameter among the stem training methods. The biggest stem diameter was recorded in the single-stem method (11.2 mm), compared to the two-plants-per-pot method (9.97 mm) and the double-stem method (9.55 mm) (Figure 2B). The stem diameter also showed a positive ($P < 0.05$) interaction between stem training method and time, where the thickness of the single-stem (12.2 mm) and double-stem training methods (10.04 mm) increased significantly in Week 7 after transplanting.

The yield and yield components varied significantly ($p < 0.05$) among the different training methods, with regard to the number of fruit and fruit mass. The single-stem training method had a significantly lower ($p < 0.05$) number of fruits per plant in each harvest (5.3), compared to the double (7.1) and two-plants-per-pot (6.6) stem-training methods. The number of fruits per plant of the two-plants-per-pot and the double-stem methods increased significantly ($p < 0.05$) in the third harvest, compared to the single-stem training method. The mass of the single-stem training method was significantly higher (138 g fruit^{-1}) than that of the double-stem training method (132 g fruit^{-1}) and the two-plants-per-pot stem methods (110 g fruit^{-1}) (Table 2). The mass of the single-stem training method was also significantly higher, from the first to the last harvest (Figure 2D).

3.3. Tomato fruit quality in response to different stem-training methods

The results showed that the interaction of stem training and time, with respect to the colour index, was significantly different ($p < 0.01$; Table 2). The general trend was that the double-stem and two-plants-per-pot methods were found to have a higher colour index in most cases,

Table 1. Responses of leaf gas exchange parameters to different stem-training methods.

Time	Treatment	A	gs	Ci	Ci/Ca	1-Ci/Ca	T
Week 3	DS	50.84b	0.463f	170.4a	0.45a	0.55f	20.46bc
	SS	47.46b	0.437f	175.6a	0.46a	0.54f	18.63abc
	TPP	47.48b	0.513f	202.1b	0.54b	0.47e	21.17c
Week 10	DS	69.98c	-	446.1f	1.21f	-0.21a	12.7a
	SS	72.42c	-	454.5f	1.23f	-0.23a	14.56
	TPP	67.76c	-	431e	1.16e	-0.16b	12.63a
Week 12	DS	36.34a	-	410.9cd	1.07c	-0.07d	16.2abc
	SS	49.56b	-	417.9d	1.11d	-0.11c	16.82abc
	TPP	39.53a	-	408.6cd	1.07c	-0.07d	13.35ab
Week 14	DS	35.73a	-	405.5cd	1.06c	-0.06d	16.44abc
	SS	35.71a	-	405.2cd	1.06c	-0.06d	16abc
	TPP	35.08a	-	404.3c	1.05c	-0.05d	15.15abc
Week 18	DS	39.91a	-	405.8cd	1.06c	-0.06d	14.12abc
	SS	40.07a	-	406.8cd	1.07c	-0.07d	16.47abc
	TPP	37.48a	-	406.6cd	1.06c	-0.06d	18.64abc
LSD		6.06	-	11.53	0.03	0.03	5.99

A: photosynthetic rate ($\mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$), gs: stomatal conductance ($\text{mmol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$), Ci: intercellular CO_2 concentration ($\mu\text{mol mol}^{-1}$), Ci/Ca: ratio of intercellular and atmospheric CO_2 concentration, 1-Ci/Ca: stomatal limitation, T: transpiration rate ($\text{mmol H}_2\text{O m}^{-2} \text{ s}^{-1}$), DS: Double stem, SS: Single stem and TPP: Two plants per pot, -: data not available.

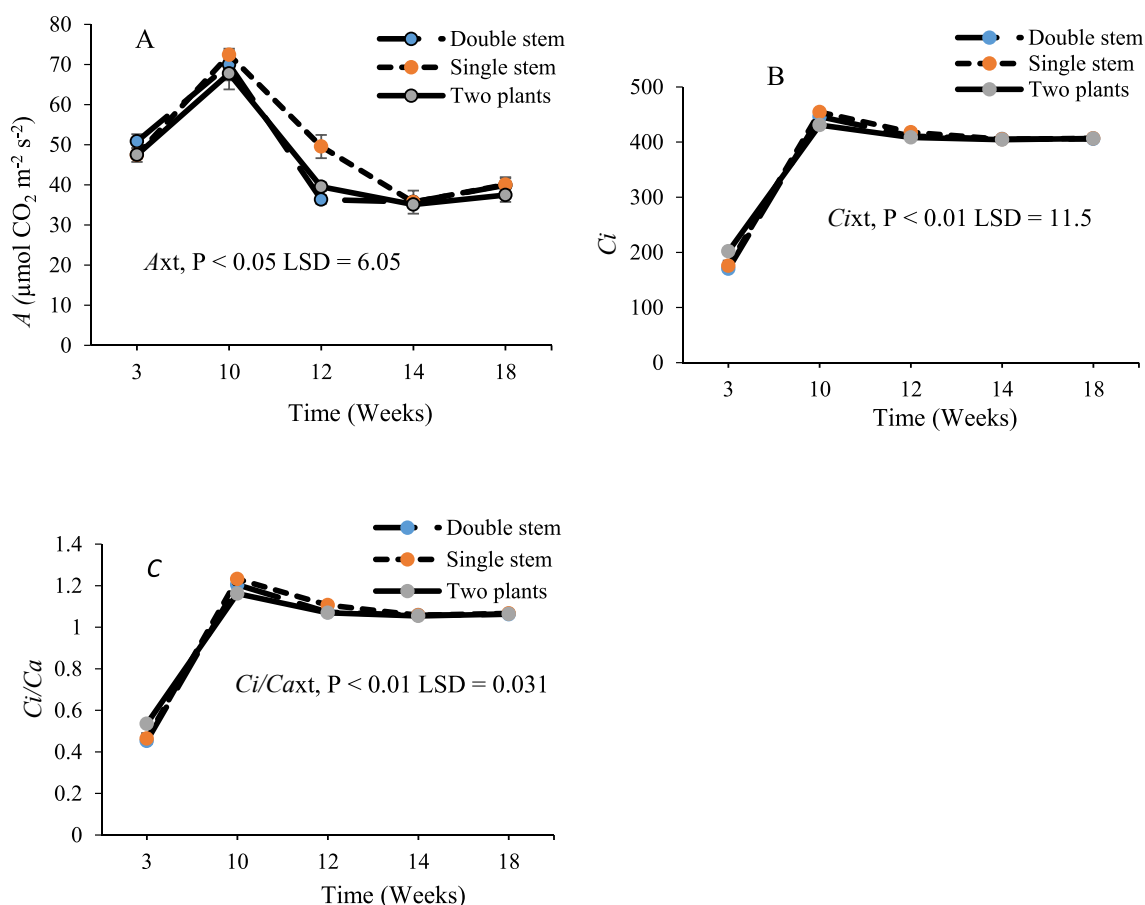


Figure 1. Responses of leaf gas exchange parameters to different stem-training methods. Photosynthetic rate (A), Intercellular CO_2 concentration (B), Ratio of intercellular and atmospheric CO_2 concentration (C).

compared to the single-stem method. The colour index varied significantly ($p < 0.05$) with the time of the sampling; an increase was observed in Harvests 1 and 2 and it declined in Harvest 3 in all treatments (Figure 3A). The results showed that the TSS was significantly higher (p

< 0.05) in the double-stem and two-plants-per-pot training methods than that in the single-stem method (Table 2). The TSS was observed to decline over time, in all the training methods (Figure 3A). Similar trends were observed in the TA in all training methods, where the single-stem

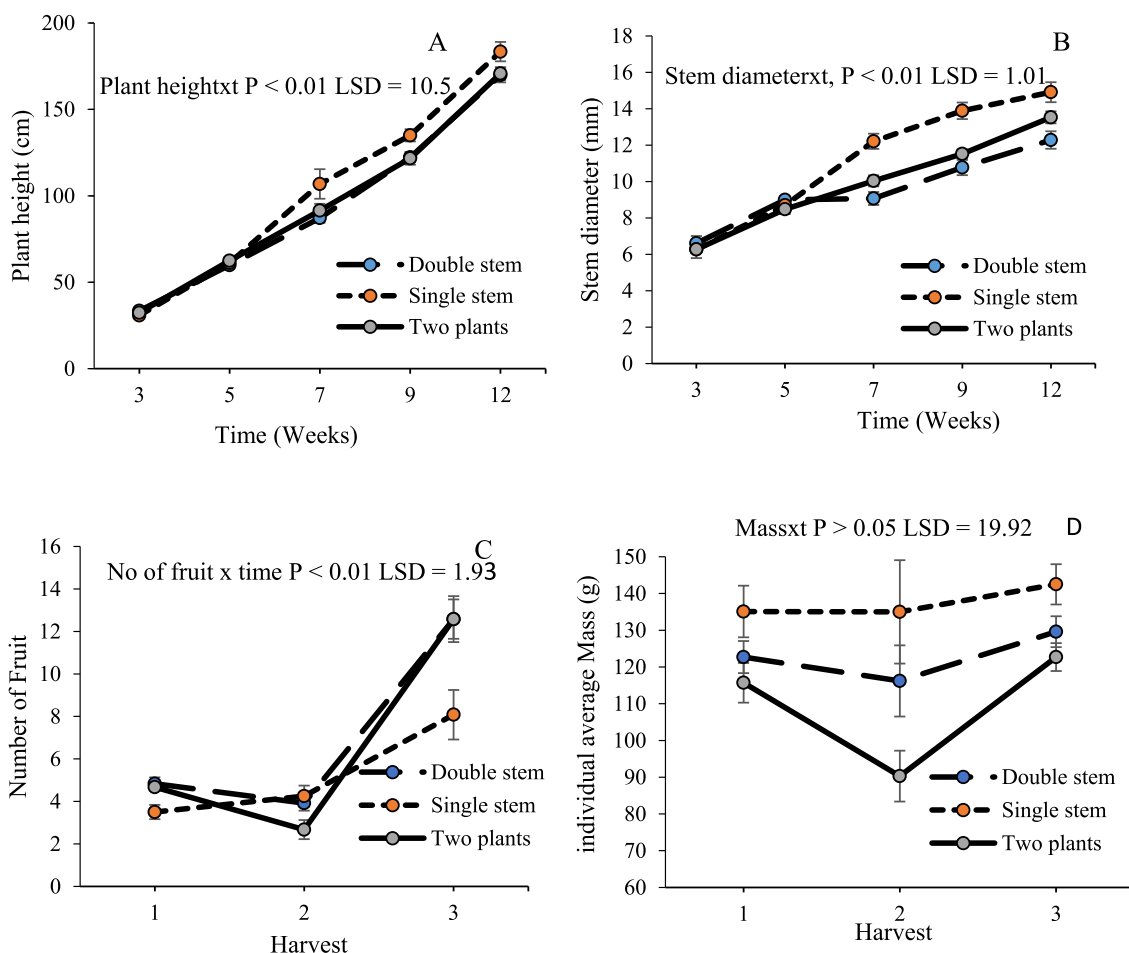


Figure 2. Effect of different stem-training methods on the growth and yield of indeterminate tomato produce in dome-shaped tunnels. Plant height (A), Stem diameter (B), Number of fruit (C) and Fruit mass (D).

Table 2. Fruit quality parameters responses to different stem-training methods.

Time	Treatment	CI	TSS	TA	BrimA
Harvest 1	DS	18.8bc	4.6c	0.3d	2.7c
	SS	12.9b	4.2b	0.25abc	2.54b
	TPP	27.8c	4.6c	0.29cd	2.78c
Harvest 2	DS	26c	4.7c	0.26bcd	2.83c
	SS	19bc	4.2b	0.23ab	2.54b
	TPP	26.4c	4.5c	0.26bcd	2.73c
Harvest 3	DS	-1.5a	4ab	0.24abc	2.41ab
	SS	2.1a	3.8a	0.22a	2.29a
	TPP	-3.4a	3.8a	0.26bcd	2.28a
LSD		9.22	0.24	0.04	0.15

CI: Colour index, TSS: Total soluble solids (°Brix), TA: Titratable acids (%), BrimA.

training method had a significantly lower TA than the two-plants-per-pot and double-stem training methods (Table 3), while the TA was also found to decrease with time (Figure 3C). A lower BrimA was observed in the single-stem training method, which had a value of 2.46, compared to 2.60 and 2.67, respectively, in the two-plants-per-pot and the double-stem training methods (Table 2). BrimA was also observed to decrease over time, where a single stem training method was lower than that of the other treatments (Figure 3D).

3.4. The correlation amongst the plant growth and leaf gas exchange parameters

The correlation coefficients showing the level of association between the plant growth and leaf gas exchange parameters that were tested in the different stem training methods are presented in Table 3. In the single-stem method, the plant height was positively and non-significantly correlated to A (0.73; P > 0.05), but negatively correlated to WUE (-0.78; P > 0.05). The stem diameter was positively and non-significantly correlated to Ci (0.85; P > 0.05), Ci/Ca (0.86; P > 0.05), but negatively and non-significantly correlated to 1-Ci/Ca (-0.85; P > 0.05) when using the single-stem method. This single-stem training method on A showed a positive and significant correlation to T (0.99; P < 0.05), Ci (0.96; P < 0.05), Ci/Ca (0.98 < 0.05), but a negative and non-significant correlation to WUE (-0.99; P < 0.05), 1-Ci/Ca (-0.98; P < 0.05). T exhibited a positive and significant correlation to Ci/Ca (0.99; P < 0.05), but a negative and significant correlation to WUE (-0.97; P < 0.05), 1-Ci/Ca (-0.99; P < 0.05) for the single-stem training method.

In terms of the two-plants-per-pot training method, the plant height exhibited a positive and non-significant correlation to A (0.76; P > 0.05). On the other hand, the plant height correlated negatively and non-significantly to WUE (-0.79; P > 0.05). The stem diameter correlated negatively and non-significantly to Ci (-0.86; P > 0.05), Ci/Ca (-0.78; P > 0.05) for the two-plants-per-pot method. A correlated positively and non-significantly with Ci (0.74; P > 0.05), Ci/Ca (0.84; P > 0.05), but correlated negatively with 1-Ci/Ca (-0.84; P > 0.05). T of the two-plant-

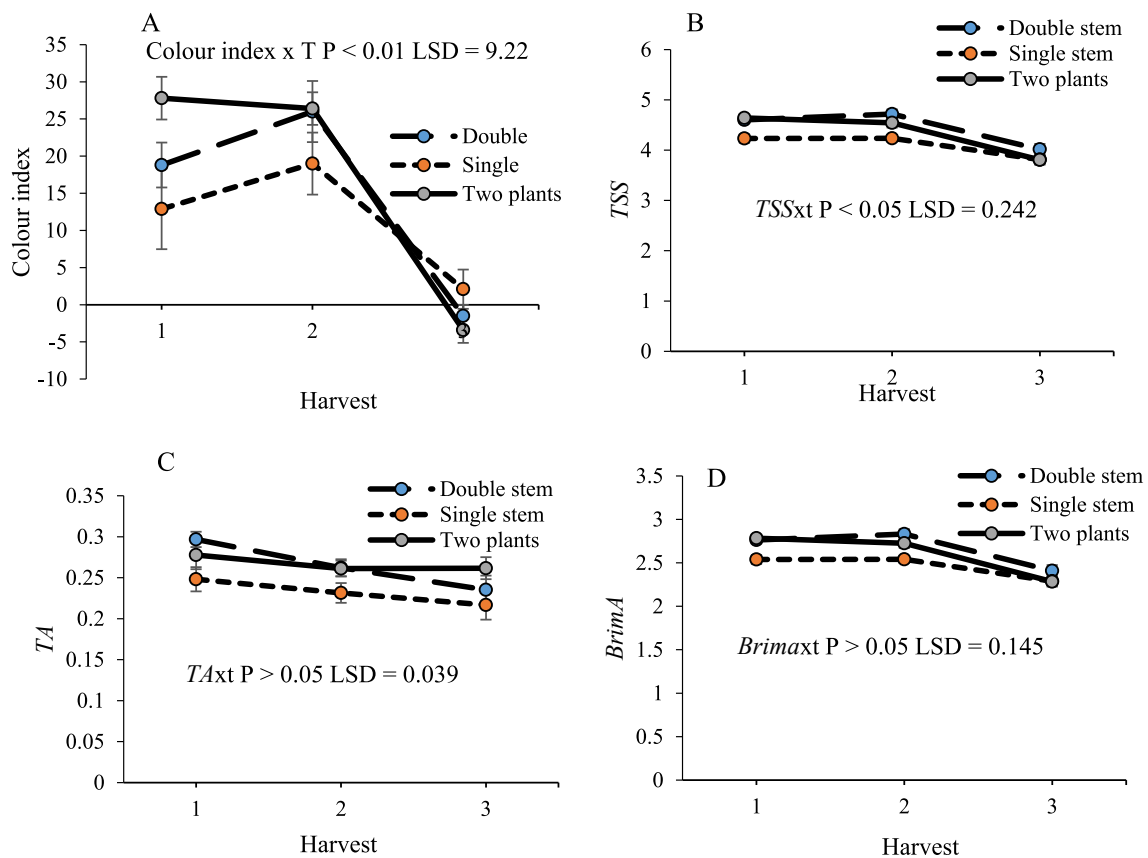


Figure 3. Fruit quality parameters in response to different stem-training methods at different harvest times. Colour index (A), Total soluble solids (B), Titratable acids (C) and Brima (D).

per-pot method correlated positively and significantly to Ci/Ca (0.95; $P < 0.05$); however, it correlated negatively and significantly to WUE (-0.95 ; $P < 0.05$) and $1-Ci/Ca$ (-0.95 ; $P < 0.05$).

The double-stem training method revealed that the plant height correlated positively and non-significantly to T (0.83; $P > 0.05$), but that it correlated negatively and non-significantly to WUE (-0.91 ; $P > 0.05$). The stem diameter correlated negatively and significantly to Ci (-0.88 ; $P > 0.05$) in the double-stem method, while the double-stem training exhibited that A correlated positively and non-significantly to Ci (0.88; $P > 0.05$). T of the double-stem training method correlated negatively and significantly to WUE (-0.98 ; $P < 0.05$). The double-stem training method showed that Ci correlated positively and significantly to Ci/Ca (1; $P < 0.05$).

4. Discussion

Understanding the physiological mechanism that plays an essential role in plant photosynthesis, growth, and yield is crucial for the selection of suitable cultural practices. The present study evaluated different stem-training methods on the leaf gas exchange of indeterminate tomatoes produced in dome-shaped tunnels, in order to identify the most promising stem training methods for improving the yield. The observed results showed a slightly higher A in the single- and double-stem training methods, compared to that of the two-plant-per-pot training method. It is hypothesized that this variation is linked to the competition for water and nutrient absorption, due to root proliferation. Two-plant-per-pot stem-training method form a root-bound at a later stage of growth, thus resulting in poor aeration within the roots (Peterson et al., 1991). Poor aeration inhibits the formation of adventitious roots that promote water uptake within the plant, and this results in a reduced photosynthetic rate (Peterson et al., 1991).

A variation was observed in A during the time of sampling, as it increased in all the treatments after transplanting, and then declined in Week 10. This sudden change in A can be associated with the change in the seasons, from summer to autumn.

The observed results also showed insignificant differences in the Ci and Ci/Ca of the different stem-training methods. The Ci determines the amount of CO_2 available in the intracellular spaces of the leaf. When the stomata open, it automatically increases the entry of CO_2 and results in an increase in the Ci concentration required for the assimilation of carbohydrates (Shezi et al., 2019). The results showed that there were significant differences between the time of evaluation on the Ci and Ci/Ca . These parameters were increased from the time of transplant and showed a slight decrease in Week 12 until the end of the evaluation, when the hypothesis was impacted by the change in the sun's position.

The current study found no significant differences among the effects of the stem-training methods on T , which means that the tested plants were not affected by them. Transpiration is the loss of water vapour through the stomata, and an increase in the stomatal pore openings means an increase in the loss of water during transpiration (Shezi et al., 2019). Water Use Efficiency (WUE), which is the ratio of water used by the plant during metabolism to the water loss by the plant through transpiration, is another factor that plays a huge role in photosynthetic efficiency, particularly in C3 plants (Shezi et al., 2019). The correlation coefficient of the present study shows a negative correlation between the T and WUE , which means that the increase in transpiration reduces the water use efficiency. The current study found no significant difference with regard to WUE , which suggests that there were no variations in the tested plants of the different stem-training methods.

The current study also showed significant differences between the growth and yield parameters in response to the different stem training methods. The observed results showed an increase in the plant height and

Table 3. Correlation coefficients of leaf gas exchange and plant growth parameters in different stem-training methods.

Parameter	Single stem		Two plants per pot		Double stem	
	P-value	r	P-value	r	P-value	r
Plant height vs Ci	P > 0.05	0.55	P > 0.05	0.53	P > 0.05	0.30
Plant height vs Ci/Ca	P > 0.05	0.61	P > 0.05	0.40	P > 0.05	0.30
Plant height vs 1-Ci/Ca	P > 0.05	-0.61	P > 0.05	-0.39	P > 0.05	-0.30
Plant height vs A	P > 0.05	0.73	P > 0.05	0.76	P > 0.05	-0.59
Plant height vs WUE	P > 0.05	-0.78	P > 0.05	-0.79	P > 0.05	-0.91
Plant height vs T	P > 0.05	0.68	P > 0.05	0.59	P > 0.05	0.83
Stem diameter vs Ci	P > 0.05	0.85	P > 0.05	-0.86	P > 0.05	-0.88
Stem diameter vs Ci/Ca	P > 0.05	0.85	P > 0.05	-0.78	P > 0.05	0.30
Stem diameter vs 1-Ci/Ca	P > 0.05	-0.85	P > 0.05	0.78	P > 0.05	-0.65
A vs Ci	P < 0.05	0.96	P > 0.05	0.74	P > 0.05	0.88
A vs T	P < 0.05	0.99	P > 0.05	0.64	P > 0.05	-0.33
A vs Ci/Ca	P < 0.05	0.98	P > 0.05	0.84	P > 0.05	0.58
A vs WUE	P < 0.05	-0.99	P > 0.05	-0.39	P > 0.05	0.44
A vs 1-Ci/Ca	P < 0.05	-0.98	P > 0.05	-0.84	P > 0.05	-0.58
T vs WUE	P < 0.05	-0.97	P < 0.05	-0.95	P < 0.05	-0.98
T vs Ci/Ca	P < 0.05	0.99	P < 0.05	0.95	P > 0.05	0.49
T vs 1-Ci/Ca	P < 0.05	-0.99	P < 0.05	-0.95	P > 0.05	-0.49
Ci vs Ci/Ca	P < 0.05	-0.99	P < 0.05	0.99	P < 0.05	1
Ci vs 1-Ci/Ca	P < 0.05	-1	P < 0.05	-1	P < 0.05	-1
Ci vs WUE	P > 0.05	-0.92	P < 0.05	-0.95	P < 0.05	-0.36
Ci vs T	P < 0.05	0.99	P < 0.05	0.99	P < 0.05	0.39

A: photosynthetic rate ($\mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$), Ci: intercellular CO_2 concentration ($\mu\text{mol mol}^{-1}$), Ci/Ca: ratio of intercellular and atmospheric CO_2 concentration, 1-Ci/Ca: stomatal limitation, T: transpiration rate ($\text{mmol H}_2\text{O m}^{-2} \text{ s}^{-1}$), WUE (kg.m^3).

stem diameter of the single-stem method, compared to that in the double- and two-plants-per-pot stem methods. Similarly, Ara et al. (2007) found that the plant height of the BARI hybrid tomato cultivar increased more when using the single-stem training method than when using the two-plants-per-pot stem method. This increase in the plant height is attributed to the lower competition for light intensity, as well as the lower uptake of water and nutrients by the plant, which plays a critical role in plant growth. The observed results also exhibited a higher number of fruits in the plants using the double- and two-plants-per-pot stem training methods, compared to those using the single-stem training method. These results were in agreement with those of Maboko et al. (2011) on the FA593 tomato cultivar, which found that the double- and two-plants-per-pot stem-training methods had a higher number of fruit, compared to the single-stem training method.

An increase in the number of stems growing from a plant also increases the number of fruits on that plant. Therefore, the double- and two-plants-per-pot stem-training methods produced a higher number of fruits per plant because they had two leader stems. On the other hand, the single-stem method had higher vegetative growth, which is associated with the promotion of flower abortion as a result of poor air circulation within the plant leaf canopy, thus reducing the number of fruits. The study also found a higher fruit mass when using the single-stem method than when using the double- and two-plants-per-pot stem training methods. Similar results were found for the FA593 (Maboko et al., 2011) and BARI tomato cultivars (Ara et al., 2007), where the single-stem method had a higher fruit mass than the two-plants-per-pot method. The increase and decrease in fruit mass correlates with a balance between the sink and source strength. In a source-limited situation, the

carbohydrate content in the plants might be low, as plants have sufficient sinks to utilize the produced assimilates (Li et al., 2015).

In addition, the study showed significant differences among the quality parameters, which suggests that the tested plants had varying responses to the stem-training methods. The colour index of the two-plants-per-pot and the double-stem training methods was higher, compared to that of the single-stem method. These findings indicate that fruit harvested from these two training methods were riper than those harvested from a single-stem training method. The early ripening in the two-plants-per-pot and double-stem training methods was hypothesized to be linked to the exposure of the fruit to high light intensity, since the plants using these methods had a lower vegetative growth. The observed results also showed a high colour index from Harvests 1 and 2, and a decline in Harvest 3, for all treatments. The decline in Harvest 3 was hypothesized to be the result of an increased number of fruits. A high fruit load increases the sink strength, which results in the competition between the assimilates.

The results also showed that there was a high TSS among the double- and two-plants-per-pot stem-training methods, compared to the single stem-training method. The TSS is the sum of the sugars, acids and other minor components in the tomato fruit (Balibrea et al., 2006). It is determined by the dry matter content and is inversely proportional to the fruit size. Beckles (2012) reported that large-sized tomatoes have a low TSS, while small tomatoes have a high TSS. This report was in agreement with the present study, where the double- and two-plants-per-pot stem training methods had smaller fruit, accompanied by a high TSS, compared to the single-stem method. The observed results also showed that the TSS showed a similar trend with respect to the colour index during the time of evaluation. This means that the TSS was also dependent on fruit ripening.

The TA determines the estimation of the acids that are available in the fruit. The TA in the tomato fruit decreases, as its maturity increases (Anthon et al., 2011), which is in agreement with the present study, where the increase and decrease of the colour index of the fruit were accompanied by an increase and decrease in the TA. The two-plants-per-pot and double-stem training methods had a higher TA than the single-stem method. The decrease of TA in the single-stem method was linked to the fruit size, because bigger fruit has a higher water content, which results in a reduction the sugars within the fruit. *BrimA* measures the balance between the acidity (sourness) and Brix (sweetness) (Jordan et al., 2001; McDonald et al., 2013). The study by Jordan et al. (2001) reported that the flavour of the fruit was more closely related to *BrimA* than the *SSC/TA*, and that it varied with the fruit type. Therefore, this index is considered to be a more superior indicator of the eating quality of horticultural fresh produce than the traditional Brix-to-Acid ratio. The present study found that double-stem and two-plant-per-pot methods had a higher *BrimA*, which means that the tomatoes that are produced by using these methods are sweeter than those using the single-stem training method.

5. Conclusion

To conclude, the current study has shown that stem training influences the plant growth, yield and physiological performance of tomatoes grown in dome-shaped tunnels. The single-stem and double-stem training methods showed a high photosynthetic rate, compared to the two-plants-per-pot method. As expected, the double-stem and two-plants-per-pot methods produced a higher number of fruit than the single-stem method. On the other hand, the fruit mass of the double-stem and two-plants-per-pot methods were lower, compared to the single-stem method, which makes them less susceptible to fruit cracking. Therefore, the results that are presented reveal that the double-stem and two-plants-per-pot training methods are the best methods for farmers who seek to optimize their yields and maximize their profits. However, it is necessary for more research to be conducted that focuses on stem training among different cultivars.

Declarations

Author contribution statement

Mlungisi F. Mngoma: Conceived and designed the experiments; Performed the experiments.

Lembe S. Magwaza; Asanda Mditshwa: Conceived and designed the experiments.

Nkanyiso J. Sithole; Shirly T. Magwaza: Contributed reagents, materials, analysis tools or data.

Samson Z. Tesfay; Khayelihle Ncama: Analyzed and interpreted the data; Wrote the paper.

Funding statement

This work was supported by National Research Foundation (NRF) of South Africa, Moses Kotane Institute (MKI) and University of KwaZulu Natal (UKZN), College of Agriculture, Engineering and Sciences.

Data availability statement

Data included in article/supplementary material/referenced in article.

Declaration of interests statement

The authors declare no conflict of interest.

Additional information

No additional information is available for this paper.

References

- Alam, M., Islam, N., Ahmad, S., Hossen, M., Islam, M., 2016. Effects of different staking methods and stem pruning on the yield and quality of summer tomatoes. *Bangladesh J. Agric. Res.* 41, 419–432.
- Amundson, S., Deyton, D.E., Kopsell, D.A., Hitch, W., Moore, A., Sams, C.E., 2012. Optimizing plant density and production systems to maximize the yield of greenhouse-grown 'Trust' tomatoes. *Hort Technology* 22, 44–48.
- Anthon, G.E., LeStrange, M., Barrett, D.M., 2011. Changes in pH, acids, sugars and other quality parameters during the extended vine holding of ripe processing tomatoes. *J. Sci. Food Agric.* 91, 1175–1181.
- Ara, N., Bashar, M., Begum, S., Kakon, S., 2007. Effect of spacing and stem pruning on the growth and yield of tomatoes. *Int. J. Sustain. Crop Prod.* 2, 35–39.
- Balibrea, M.E., Martínez-Andújar, C., Cuartero, J., Bolarin, M.C., Pérez-Alfocea, F., 2006. The high fruit soluble sugar content in wild *Lycopersicon* species and their hybrids with cultivars depends on sucrose import during ripening, rather than on sucrose metabolism. *Funct. Plant Biol.* 33, 279–288.
- Beckles, D.M., 2012. Factors affecting the postharvest soluble solids and sugar content of the tomato (*Solanum lycopersicum* L.) fruit. *Postharvest Biol. Technol.* 63, 129–140.
- Dong, C., Shao, L., Wang, M., Liu, G., Liu, H., Xie, B., Liu, H., 2016. Wheat carbon dioxide responses in space simulations conducted at the Chinese Lunar Palace-1. *J. Agron.* 108, 32–38.
- Hobson, G.E., Adams, P., Dixon, T.J., 1983. Assessing the colour of the tomato fruit during ripening. *J. Sci. Food Agric.* 34, 286–292.
- Jordan, R.B., Seelye, R.J., McGlone, V.A., 2001. A sensory-based alternative to the brix/acid ratio. *Food Technol.* 55, 36–44.
- Li, T., Heuvelink, E., Marcelis, L.F., 2015. Quantifying the source-sink balance and carbohydrate content in three tomato cultivars. *Front. Plant Sci.* 6, 416.
- Lopez Camelo, A.F., Gómez, P.A., 2004. Comparison of color indexes for tomato ripening. *Hortic. Bras.* 22, 534–537.
- Maboko, M., du Plooy, C., 2009. Effect of stem and fruit pruning on the yield and quality of hydroponically-grown tomatoes. *Afr. Crop Sci. Conf. Proceed.* 9, 27–29.
- Maboko, M., du Plooy, C., Chiloane, S., 2011. Effect of plant population, fruit and stem pruning on the yield and quality of hydroponically-grown tomatoes. *Afr. J. Agric. Res.* 6, 5144–5148.
- Maboko, M., du Plooy, C.D., 2008. Effect of pruning on the yield and quality of hydroponically-grown cherry tomatoes (*Lycopersicon esculentum*). *S. Afr. J. Plant Soil* 25, 178–181.
- Mashilo, J., Odindo, A.O., Shimelis, H.A., Musenge, P., Tesfay, S.Z., Magwaza, L.S., 2017. Drought tolerance of selected bottle gourd [*Lagenaria siceraria* (Molina) Standl.] landraces assessed by leaf gas exchange and photosynthetic efficiency. *Plant Physiol. Biochem.* 120, 75–87.
- McDonald, H., Arpaia, M.L., Caporaso, F., Obenland, D., Were, L., Rakovski, C., Prakash, A., 2013. Effect of gamma irradiation treatment at phytosanitary dose levels on the quality of 'Lane Late' navel oranges. *Postharvest Biol. Technol.* 86, 91–99.
- Ncama, K., Opara, U.L., Tesfay, S.Z., Fawole, O.A., Magwaza, L.S., 2017. Application of Vis/NIR spectroscopy for predicting sweetness and flavour parameters of 'Valencia' orange (*Citrus sinensis*) and 'Star Ruby' grapefruit (*Citrus x paradisi* Macfad). *J. Food Eng.* 193, 86–94.
- Obenland, D., Collin, S., Mackey, B., Sievert, J., Fjeld, K., Arpaia, M.L., 2009. Determinants of flavor acceptability during the maturation of navel oranges. *Postharvest Biol. Technol.* 52, 156–163.
- Peterson, T.A., Reinsel, M.D., Krizek, D.T., 1991. Tomato (*Lycopersicon esculentum* Mill., cv. 'Better Bush') plant response to root restriction. *J. Exp. Bot.* 42, 1241–1249.
- Shezi, S., Magwaza, L.S., Mashilo, J., Tesfay, S.Z., Mditshwa, A., 2019. Photosynthetic efficiency and relationship to the mesocarp dry matter content of 'Carmen' avocado (*Persea americana* Mill.) fruit in a cool subtropical climate. *Sci. Hortic.* 253, 209–216.
- Shi, K., Ding, X.-T., Dong, D.-K., Zhou, Y.-H., Yu, J.-Q., 2008. Root restriction-induced limitation to photosynthesis in tomato (*Lycopersicon esculentum* Mill.) leaves. *Sci. Hortic.* 117, 197–202.
- Snyder, R., 2007. *Greenhouse Tomato Handbook*. Mississippi State (Starkville). Mississippi State University Extension.