Investigating the effect of trellising and stem training methods on the horticultural performance of indeterminate tomatoes grown in dome shape tunnels

by

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PREFACE

The research contained in this thesis was completed by the candidate while based in the Discipline of Horticulture Science, School of Agricultural, Earth and Environmental Sciences of the College of Agriculture, Engineering and Science, University of KwaZulu-Natal, Pietermaritzburg campus, South Africa. The research was financially supported by the National Research Foundation and Moses Kotane Institute.

The contents of this work have not been submitted in any form to another university and, except where the work of others is acknowledged in the text, the results reported are due to investigations by the candidate.

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DECLARATION

I, Mlungisi Fihlane Mngoma, declare that:

(i) The research reported in this thesis, except where otherwise indicated or acknowledged, is my original work;

(ii) This thesis has not been submitted in full or in part for any degree or examination to any other university;

(iii) This thesis does not contain other persons' data, pictures, graphs or other information, unless specifically acknowledged as being sourced from other persons;

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(vi) This thesis is primarily a collection of material, prepared by myself. In some cases, additional material has been included;

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Abstract

Growing of tomato in open field in South Africa is very challenging due to unfavorable environmental conditions, pests and diseases. This has resulted to an increased hydroponic production of tomatoes in protected cultivation. However, protected cultivation require many horticultural practices for optimum production. The first experiment of the study was conducted to evaluate the effect of different trellising methods namely, early layering, late layering and vertical trellising in response to leaf gas exchange and chlorophyll fluorescence of indeterminate tomato produced in tunnels. The second experiment was conducted to assess the effect of trellising method on growth, yield and quality parameters of indeterminate tomato. The third experiment investigated effects of different stem training methods namely, single stem, double stem and two plant per pot in line with growth, yield and physiological responses of indeterminate tomato grown in dome shape tunnels.The results of the first study showed that early and late layering increase photosynthetic rate (*A*), transpiration rate (*T*), the effective quantum efficiency of photosystem II photochemistry (*ΦPSII*) and electron transportation rate (*ETR*) compare to vertical trellising. The second study revealed that early and later layering increase plant height, number of fruit and fruit mass compare to vertical trellising. However observed results showed no variation among trellising methods with quality parameters. The third experiment on leaf gas exchange results showed high photosynthetic rate (*A*) and stomatal conductance (*gs*) in single and two plants per pot stem. Single stem exhibited high plant height and stem diameter with double and two plants per pot stem. Single stem and double stem showed high number of fruits, and fruits mass compare to two plants per pot stem training. The study also showed high colour index, total soluble solids (*TSS*), titratable acids (*TA*), and BrimA with double stem and two plants per pot than single stem.

Therefore, the presented results revealed that early and late layering trellising methods can be the best methods that can be used by resource-constrained farmers in dome shape tunnel to increase physiological efficiency, growth and yield. On the other hand double stem and two plants per pot training method can had a potential to improve yield and quality of indeterminate tomato grown in tunnel.

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Table of Contents

Chapter 1: General introduction

1.1 Background

Tomato (*Solanum lycopersicum* Mill.) is regarded as one of the horticultural crops with two types of growth habits, namely determinate and indeterminate. In most cases, determinate tomatoes are planted in open fields while indeterminate tomatoes, on the other hand, are mostly planted under protected cultivation. Tomato production has long been regarded as one of the strategies for improving food security and nutrition, increase job opportunities and improve economy of the South Africa (Ssekyewa, 2006). Tomato fruits have many health benefits in human body and; hence, it contributes to a balanced diet. This is mainly because tomatoes have high nutrients such as, vitamin A, C and E (Beecher, 1998). On average, tomatoes provide vitamin C estimated to 20 mg per 100 mg of product edible (Willcox et al., 2003). Mature tomato at breaker stage of ripening, 145 mg provide daily allowance of vitamin C up to 40 percent and 20 percent of vitamin A (Kelley et al., 2010). Tomato fruit contain pigments such as, lycopene, carotenoids which act as natural anti-oxidant, niacin, calcium, water, which are important for metabolism in human body (Olaniyi et al., 2010).

In terms of world production, China, India, United States, Turkey and Egypt are the largest producers of tomato (FAO, 2014). In 2014, these countries contributed 62% of the world total tomato production with an annual average yield of 52.6 MT,18.7 MT, 15.9 MT,11.9 MT and 82.9 MT respectively (FAO, 2014). Production of tomato in Southern African Development Corporation (SADC) is increasing, however, South Africa regarded as the highest producer which produced 54% of tomato on 11% of the total crop area (FAO, 2014). All provinces of South Africa produce tomatoes with Limpopo province being the major producer (Sigidi, 2017). The temperature in Limpopo is very hot and dry. These factors encourage the increase of tomato success because low humidity discourages pests and diseases build up. The total area planted with tomato in Limpopo is 3 590 ha, which is 75% of the country's total area under tomato production. Tomato production in winter is very limited and the price is very high because tomato can only be planted under protected cultivation systems in tunnels and greenhouses or frost free areas (Sigidi, 2017).

Growing crops in tunnel structures has many benefits of controlling adverse weather conditions associated with outdoor crop production. Many farmers in South Africa are exploring tunnel production to grab the opportunity of market gab available during winter months (Carey et al., 2009). This production system, benefits farmers to sell their produce out of season, increase production, reduce the risk of pest an diseases and improve quality. However, producing tomatoes in a tunnel require good management of horticultural practices for optimum production such as transplanting, pruning, trellising, stem training and fertigation. Trellising is one of the most common cultural practices used to improve yield and quality. Trellising is the used of strong material to support tomato plants since it is tender to keep fruits and foliage off the ground, enhances better aeration on foliage, a good light interception on the foliage and also protect the plants from diseases (Saunyama and Knapp, 2003). There are different types of trellising methods used for tomato production, however, the common used for tunnel production are vertical trellising, early and late layering. This trellising method is achieved by hanging tomato plant on a horizontal wire running on top of the plant at a height of ±2 m using twines and hangers. These trellising methods are different in trellising positions. Vertical trellising achieved by trellising plant in upward position while early layering achieved by trellising plants in a diagonal direction. Late layering is the combination of vertical and early layering trellising. Late layering plants are trellised upright from transplant until they reach the maximum height of the tunnel and late trellised in a diagonal direction.

Vertical trellising is the most common trellising method use in commercial tunnel production systems since they have high roofs and system to filter solar radiation. However, the use of this trellising method in small-scale systems using dome-shaped tunnel structures has height limitations because tomatoes grow tall up to a maximum height of 6 m. Dome-shape plastic tunnels are usually available at a maximum height of 3 m tall. Therefore tomato plants reach the maximum height of the tunnel before producing to it is optimum yield. The temperature at the highest level of the tunnel is very high, especially during the hot summer days (Owen et al., 2016). It has been observed that apical meristem at high temperatures are burnt by the heat of the plastic roof and plants end up dying earlier before the crop has produced its potential yield.

Layering trellising has been identified as an alternative method to solve the problems associated with height and is known to improve yield and quality of tomato produced in dome-shaped tunnels (Lecuona, 2013). However, some farmers use this method and reported improvement of crop lifespan but no increase in yield. The decrease in yield hypothesis to be linked to the timing of trellising because most farmers allow plants to reach the maximum height of the tunnel before the application of layering trellising. Late application of layering changes the original orientation of tomato plant which might also influence the partitioning of the vascular system. Furthermore, this trellising method causes mechanical damage to the plant which might also have a negative effect on plant physiology.

Other cultural practices commonly used during production of indeterminate tomato in tunnel is stem training method (Snyder, 2007). Stem training is defined as the number of stem allowed to grow as a leader stem during plant growth. There are different types of stem training used for tomato production which includes, single stem, two plants per pot and double stem. A single stem is achieved by planting one seedling per pot and remove all suckers stem growing whereas two plants per pot achieve by planting two seedlings per pot and remove all suckers. Double stem on the other hand is achieved by planting one seedling per pot and allow the sucker to grow as a second leader stem.

Stem training exhibit different leaf area index and percentage of leaves exposure to the sunlight which affects plant physiology and yield. On the other hand stem training also affect the root density of tomato plants, for example, two plants per pot method at a later stage form root ball and resulting to decrease water absorption in the roots (Shi et al., 2008). Therefore poor absorption of water and nutrients by the roots may also impact other numerous variables such as water use efficiency, transpiration and fruit formation.

Single stem training method is commonly used in South Africa for the production of indeterminate tomato produce in tunnels (Snyder, 2007). Tomato plants propagated with this method produce large and high fruit mass (Snyder, 2007). However, tomatoes produced with this training method have been reported to have a low marketable fruit and very susceptible to fruit cracking (Maboko and Du Plooy, 2009). On the other hand, this training method produces a low number of fruit per plant and large fruit which hypothesis to be the main cause of fruit cracking, thus, resulting in a reduction of marketable fruits (Maboko et al., 2011). Therefore farmers are trying to optimize their yield by shifting from a single stem to two plants per pots. However, two plants per pot method have no impact on increasing farmers' profit Amundson et al. (2012). This steadiness in profit hypothesis to be associated with the additional cost incurred when increasing the number of seedlings. These costs include inputs costs such as seedling, fertigation, maintenance and labour cost.

Growing tomatoes as a double stem has been identified as an alternative method for solving the problem associated with low yield and known to reduce the cost incurred during production. Alam et al. (2016) found that tomato of BARI hybrid produced with double stem had high fruit mass compared to a single stem. Maboko et al. (2011) reported that tomato (FA593) produced in a double stem method had a high yield and a high number of marketable fruit compared to a single stem. Amundson et al. (2012) found that the two plants per pot method had a high yield of tomato during summer compared to a double stem method, whereas, there was no significant difference in winter. The findings reported by authors necessitate more research since there is no clear information on the yield of double stem and two plants per pot.

1.2 Research aim

- This study aims to generate knowledge that will contribute further understanding the effect of different horticultural practices on plant growth, development, physiology, yield and quality response of indeterminate tomato produced in tunnel produced tomatoes.

1.3 The specific objectives were to:

1. Investigate gaseous exchange and photosynthetic efficiency of fertigated indeterminate tomatoes in response to trellising methods
2. Assess the influence of trellising methods on growth, yield and quality of indeterminate tomato produced in dome shape tunnels.
3. Evaluate the effects of stem training on physiology, growth, and yield responses of indeterminate tomato plants grown in protected cultivation

1.4 References

Alam, M., Islam, N., Ahmad, S., Hossen, M. & Islam, M. 2016. Effect of different staking methods and stem pruning on yield and quality of summer tomato. Bangladesh Journal of Agricultural Research, 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 yield of greenhouse-grown 'Trust'Tomatoes. Horticultural Technology, 22**,** 44-48.

Beecher, G.R. 1998. Nutrient content of tomatoes and tomato products. Proceedings of the Society for Experimental Biology and Medicine, 218**,** 98-100.

Carey, E.E., Jett, L., Lamont, W.J., Nennich, T.T., Orzolek, M.D. & Williams, K.A. 2009. Horticultural crop production in high tunnels in the United States: A snapshot. Horticultural Technology, 19, 37-43.

FAO. 2014. Food and Agriculture Organization (FAO) of the United Nations. Production quantities of tomato in the world. http://www.fao.org/faostat/en/#data/QC/visualize. Last accessed 15 July 2018

Kelley, W.T., Boyhan, G.E., Harrison, K.A., Sumner, P.E., Langston, D.B., Sparks, A.N., Culpepper, S., Hurst, W.C. & Fonsah, E.G. 2010. Commercial tomato production handbook, p.3

Maboko, M. & Du Plooy, C. 2009. Effect of stem and fruit pruning on yield and quality of hydroponically grown tomato. African Crop Science Conference Proceedings, 9, 27-29.

Maboko, M., Du Plooy, C. & Chiloane, S. 2011. Effect of plant population, fruit and stem pruning on yield and quality of hydroponically grown tomato. African Journal of Agricultural Research, 6, 5144-5148.

Lecuona, A. 2013. Trellising tomato plants in a greenhouse. https://www.commercial-hydroponic-farming.com/trellising-tomato-plants/. Last accessed: 20 May 2019.

Olaniyi, J., Akanbi, W., Adejumo, T. & Ak, O. 2010. Growth, fruit yield and nutritional quality of tomato varieties. African Journal of Food Science, 4, 398-402.

Owen, W.G., Hilligoss, A. & Lopez, R G. 2016. Late-season high tunnel planting of specialty cut flowers in the Midwestern United States influences yield and stem quality. Horticultural Technology, 26, 338-343.

Saunyama, I. & Knapp, M. 2003. The effects of pruning and trellising of tomatoes (*Lycopersicon esculentum Mill.*) on red spider mite (*Tetranychus evansi Baker & Pritchard*) incidence and crop yield in Zimbabwe. African Crop Science Journal, 11**,** 269-277.

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. Scientia Horticulturae, 117**,** 197-202.

Sigidi, K.Z. 2017. Hedonic price analysis of tomatoes sold by hawkers in the Vhembe District of Limpopo Province, South Africa. MSCAGR (Agricultural Economics) Thesis. University of Venda

Snyder, R. 2007. Greenhouse tomato. Handbook. Mississippi State Ext, p.1828.

Ssekyewa, C. 2006. Incidence, distribution and characteristics of major tomato leaf curl and mosaic virus diseases in Uganda. PHD Thesis. Ghent University.

Willcox, J.K., Catignani, G.L. & Lazarus, S. 2003. Tomatoes and cardiovascular health. Journal of Food Science, 43, 1-19

Chapter 2: Horticultural practices affecting growth and yield of tomatoes planted under protected cultivation: A review

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2.1 Abstract

The developing countries, such as those in sub-Saharan Africa, are faced with a many challenges when producing tomatoes in open fields. These challenges include high incidence of pests and diseases, poor crop management practices as well as changes in temperature and soil pH which are often not conducive for optimum crop growth. This has resulted in an increased hydroponic production of tomatoes in protected cultivation. The one of the most essential cultural practices used to improve yield and quality of a plant in tunnel production is the trellising of tomato plants. However, there is limited information about trellising and the best trellising methods used in tunnel production. This review discusses the application of different cultural practices including the use of different cultivars, transplanting, and type of growing media, plant population, watering and fertilization as well as giving more emphasis on trellising methods. Trellising of tomato plants is one of the most important cultural practices used to improve yield and quality in tunnel production. Notably, there is a lack of peer-reviewed information about the best trellising methods used in tunnel production. However, numerous reports from farmers seem to indicate that layering and vertical trellising are the most used methods under tunnel production. Studies have shown that tomato plants that produced fruit with high TSS tend to have a lower yield. However, although extensive research has been conducted on different cultural practices trying to improve both yield and total soluble solutes (TSS), the findings remain inconclusive. Thus, this review has indicated that there is a need for more research on trellising methods in dome shape tunnels and to identify cultural practices that could increase both TSS and yield.

2.2 Introduction

The global tomato production increased by 47% with Asia showing the increase of 87% from 2001 to 2011 (FAO, 2014). South Africa is the highest producer of tomato in sub-Saharan Africa (SSA), which is producing 54% of tomato in the total crop area of 11% (FAO, 2014). Tomato in South Africa, regarded as the second most essential vegetable crop after potato because of its perceived health benefits. The crop has been reported to contain vitamins as well as minerals and it has been identified as one of the important sources of food security and vital role in human nutrition (Salunkhe and Kadam, 1995; Shi and Maguer, 2000). Tomato is a rich source of natural anti-oxidant such as, vitamin C, lycopene, phytochemicals, folate and carotenoids which play an essential role in human body to fight against cancer (Ganesan et al., 2012).

In South Africa, with its wide diverse agro-climatic zones and soil types, growing crops such as tomato in the soil are risky and highly unpredictable. Changes in temperature, poor water holding capacity, soil pH, pest and diseases, heavy metals, proper root aeration as well as available nutrient supply are some of the challenges farmers face when producing tomatoes in the open field (Maboko et al., 2012, Du Plooy et al., 2012). As a result, hydroponics in the greenhouse has been used to counteract some of these challenges and provide the control on plant growth and development. Hydroponics in greenhouses improve the use of water and nutrients and the control of the surrounding environmental conditions (Resh, 2017), this usually results in higher yields and quality compared to traditional cultivation techniques. However, this is rarely being realized particularly by small scale farmers which often lack skills and other resources required for production.

Although the use of greenhouse production has been recognize as better option for tomato production, there are numerous horticultural practices needs to be considered for a successful production. These include transplanting, cultivars selection, growing media, watering and fertigation. Cultivars for open field do not grow well in greenhouse production (Maboko et al., 2010). Cultivars of determinate tomatoes are most commonly used for open field because of growth adaption requirements. Determinate tomatoes have a short growing lifespan, require conditions of high light and lower humidity (AgCenter, 2009). Indeterminate tomatoes on the other hand, are commonly used for greenhouse production since they have long life span and most cultivars are less susceptible to pest and diseases compare to open field cultivars (Heuvelink, 2005). Tomato seeds for greenhouse cultivation are very expensive, but it is very crucial to select quality seeds to improve growth and developmental stage...

Tomato yield and quality can be improved by trellising. Trellising is defined as the use of sturdy material to support tomato stem since it is herbaceous to keep fruit and foliage off the ground, increase light interception and reduce pest and diseases (Alam et al., 2016). There are so many different trellising methods used for tomato production such as vertical trellising, layering trellising, basket weave trellising and netting trellising (http://www.johnnyseeds.com/trellising, Accessed, 30January 2019). The most common trellising method used in protected tomato production is vertical and layering trellising (http://www.johnnyseeds.com/trellising, Accessed, 30January 2019). Both vertical and layering trellising methods are achieved by securing tomato plant with a plastic twine and hang on horizontal wire running at height of ± 2 m above the ground. However, these methods are different in trellising positions. Vertical trellising method is achieved by trellising tomato plant in a vertical direction while layering trellising method is achieved by trellising in a diagonal direction. Although there is no published work on trellising methods but communication with farmers has indicated that vertical trellising is the most efficient for commercial tunnels with high roof and system to filter solar radiation. However, in dome shape tunnels, it has height limitation, since tomato plant grows tall and reach the maximum height of the tunnel before attainment of its yield potential. Epical meristem at the maximum height of the tunnel are burnt by the heat of the plastic roof during hot days. In response to this challenge, layering trellising has been identified as an alternative method to solve this problem associated with height limitation since plants move sideways down horizontal as the plant height become close to the overhead wire. To the best of our knowledge, there is no sufficient scientific evidence to support which trellising method in dome shape tunnel has a positive influence on yield and quality of tomato. Therefore, there is an existing gap which need further investigation to identify the trellising method that has a positive influence on yield and quality of tomato produced in dome shape tunnels.

Further, the importance of high yield and good quality in production of tomato has grown in the past few years, due to competitive pressure and high demand. Total soluble solids (TSS) is one of the crucial quality parameters used for determining the taste of tomato fruits. Tomato fruits with good appearance, big size, high acid and high sweetness is regarded as best quality in customer perception. However, tomato produced for processing must have high TSS (May and Gonzales, 1993). May and Gonzales (1998) and Tüzel et al. (1993) reported that tomato plants which produce fruit with high TSS have lower yield while tomato plants which produce fruits with high yield have lower TSS. Therefore, there is a need to further investigate cultural practices that could improve both yield and TSS.

The aim of this paper is to review the effect of different horticultural practices on growth and yield of tomatoes produced in protected structures with the view to identify the best practice. Identifying the best trellising method could improve yield and quality of tomato fruits produced in dome shape tunnels. Finally, discovering the cultural practices that could improve TSS without reducing yield will improve our understanding of the best management practices that results in high quality tomato produce.

2.3 Tomato production under protected structures: an overview

The production of vegetables under protected structures has increased significantly over the past decades. The world production of vegetables under hydroponics has increased from 5000 - 6000 hacters in the 1980s to 20000-25000 hacters in year 2001 (Resh, 2016). Rodríguez-Delfín (2011), claimed that hydroponic production in the world 35000 hacters. The author also pointed out that commercial greenhouse vegetable production varies from 330 000 to 1.2 million hactares because of the definition of "greenhouse" and "hydroponic production".

Greenhouse hydroponic production is the system that produced plants in a soilless culture and not same as plastic low tunnels and poly tunnels that just covers the existing soil with a structure, water and nutrients are applied with drip irrigation systems (Resh, 2016). On the other hand, "greenhouses" which usually have computerized fertigation systems but are growing on the local soil cannot be classified as hydroponics (Resh, 2016). The former two methods described thus can be together classified as protected cultivation which can be described as a method of producing plants under a structure covered with ultraviolet (UV) stabilizer, such as plastic and glass to control environmental conditions and reduce the incidence of diseases (Peet and Welles, 2005).

The major drivers of greenhouse production is that, firstly, it separate the plant from the conditions of the environment, thus providing shelter to prevent plants from the direct influence of external weather conditions (Van Straten et al., 2010). This allows the production of crops that are not adapted to be produced at that specific location. Secondly, the greenhouse covering allows the manipulation of the plants environment hence it permit the grower to steer the cultivation in the desirable direction (Van Straten et al., 2010). This in turn leads to production of high-quality products year round and also improve the water and nutrients use efficiency and less use of protective chemicals (Jett, 2004b).

2.3.1 Greenhouse

Greenhouses are covered mainly with three types of covering materials which includes the rigid plastic, polyethylene plastic and glass. The choice of greenhouse covering are selected based on the environmental conditions of the particular area and cost consideration to the producer. Plastic film covering can be used either single or double layer. Double layer plastic are used in cold climates where it is possible to separate layer by insulating layer of air to conserve energy. Traditionally greenhouse structures were covered with glass before the appearance of plastic covering (Von Elsner et al., 2000). Glass has an advantage of high light radiation, low degradation due to environmental factors and long life span (Von Elsner et al., 2000). In many countries the use of plastic has been extensively used due to its affordability and good light transmission. Polyethylene plastic has a different formulation and advance extrusion technologies to make it possible to combine with different plastic layers to modify thermal properties (Jensen, 2001). However, the disadvantage of this is that all plastic coverings have short life span due to degradation caused by ultraviolet (UV) radiation, temperature extremes and air pollution (Von Elsner et al., 2000). Polyethylene plastic covering are generally replaced after 2 to 4 years to optimize light radiation (Peet and Welles, 2005). Rigid plastic used in the greenhouse coverings includes polycarbonate, polyester, polycarbonate, polyvinyl and acrylic. The use of rigid plastic has increased due to the efficient transmission of UV and it last longer for the period of more than 10 years. However, rigid plastics is more expensive than polyethylene plastic but less expensive than glass (Giacomelli and Roberts, 1993).

2.3.2 Tunnels

2.3.2.1 Low – tunnel

Low – tunnel is a protective growing structure established during the initial growing stage of the plant (Arin and Ankara, 2001). They are generally available at the height of about 1m and no aisle for walking. Low tunnels are globally covered with thermal film of infrared ethylene-vinlyacetate, copolymer and polyvinylchloride. The rows of vegetables are covered with a protective cover to reduce wind damage, increase temperature, and protection against frost to accelerate growth and extending the season of growth (Waterer, 1992). Low – tunnels are not feasible for controlling major frost damage since they only increase temperature by 1-2 °C (Arin and Ankara, 2001). Thus, the use of low- tunnel in tomato production increase yield in most cases and can be harvested earlier than tomato planted in open field (Arin and Ankara, 2001).

2.3.2.2 High tunnels

According to Lamont (2009), high tunnels are not greenhouses but it is difficult to distinguish between the two. The structure of high tunnels are covered with a clear polyethylene plastic of single layer and the sides are ventilated by rolling up the plastic (Lamont, 2009). High tunnels have no permanent heating and cooling system to control temperature, but there is adequate water supply through drip irrigation (Lamont et al., 2002). High tunnels are globally accepted as a production practice to extend the growing season of the crop. The growing structures extend the growing period by protecting plants against frost, rain, wind, pest and diseases. Optimal yield of tomato can be achieved through the consistent supply of water (Reeder, 2006). Tomato produced in high tunnels can be harvested 2 to 3 weeks earlier compare to plants produced in the low tunnel (Waterer, 2003). High tunnels on the other hand, can be harvested four weeks earlier than the plants produced in open fields (Wells, 1991).

2.3.2.3 Shade nets

Netting is used to reduce the amount of solar radiation receive by the crop and also protect against hail and wind. In addition, photo selective shade nets reduce the amount of light entering the greenhouse and also increase the amount of scattered light to improve the photosynthesis of the plant (Ilić et al., 2015). Although the use of shade nets is recommended for protecting tomato plants and increase the yield and quality, however, the percentage of the shade also affect the plant growth. The shade net of 35% is regarded as the best and suitable for the production of tomatoes compared with 50 and 75% shade nets (Quaglitto (1976). Nangare et al. (2015), investigated the effect of greenhouse shade nets percentage at 35, 50 and 75%, on yield of tomato. The authors found that 35% shade net improve the total yield of tomato compared to 50 and 75% which was the lowest. Similarly, Argade et al. (2018) reported that 35 % shade nets increased the yield of cherry tomato on different cultivars than 50 and 75% shade nets. Similarly Priya et al. (2002) reported on sweet pepper. Although, 35% shade net seem to be optimum for crops such as tomatoes and peppers, contradictory results have been reported in other crops. For example, Patil and Bhagat (2014) found that 50 and 75% shade nets increase yield of cucumber than 35% shade nets.

In addition, shade nets colour have an influence in specific light filtrations, which cause a modification of light quality under the nets (Shahak, 2006, Shahak et al., 2004). The quality of light can be manipulated by covering the growing structure with different coloured shade nets. Shade nets colour selection depends on plants' requirement to quantity and quality of light radiation. For example, the use of red photo-selective and pearl nets in tomato improved the fruit firmness, fruit mass, and bioactive components (Tinyane et al., 2013). Ilić et al. (2015) investigated the effect of shade nets colour on tomato (vedetta cultivar) lycopene content namely, red, black, blue, pearl and control. The authors found that shade nets of black, blue and red colour increase the lycopene content compare to pearl and control. Similarly, Lopez et al. (2006) found that the lycopene content of tomatoes grown under red shade net was higher compared to pearl shade nets. The variation in lycopene content was due to the light quality and temperature. Lycopene biosynthesis depends on temperature, it takes place at an optimal temperature of 22-26 °C (Ilić et al., 2015). Temperature above 30 °C inhibit the lycopene synthesis (Brandt et al., 2006). The results of these studies suggest the importance of choosing suitable material informed by empirical evidence.

2.4 Effect of horticultural management practices on tomato produce in protected cultivation

2.4.1 Cultivars

Selecting cultivar adapted for a particular environment is very crucial in crop establishment. This ensures higher productivity and risk reduction of crop susceptibility to pests and diseases. The most cultivars used in South Africa for commercial production of tomatoes are imported (Maboko and Du Plooy, 2014) and least is known and/reported about their comparative performance in growth, development, yield and quality parameters in the South African context. Star 9010, 9011 cultivars are the most leading South African cultivars in the fresh market (Table 1). However, for the processing market HTX14 is the most cultivar recognized as of superior quality (Table 1). Some tomato cultivars are suitable to be planted in the tunnels whereas some are suitable for open field conditions. Varieties of open field are typically adapted to higher light intensity and lower relative humid conditions and would not grow well in greenhouses because the plastic or glass houses reduce the light by 20% compared to outdoor light (Peet and Welles, 2005). In most cases, indeterminate tomatoes are used for greenhouse production because of the longevity of its life cycle while determinate is selected for an open field because of a short period of life span which makes it possible to harvest before disease infestation (Peet and Welles, 2005). Protected cultivation in South Africa, has gained popularity in recent years due to improved growth, quality and yield. While the majority of producers cultivate tomatoes in an open field, a small amount is produced in the soilless production system under a protected environment (Maboko et al., 2010). The yield of tomato grown in open fields has been observed to be lower than those produced in soilless production systems under a protected environment for different cultivars. For example, (Maboko et al., 2010) compared four tomato cultivars, namely, FA593, Malory, FiveOFive and Miramar on yield and quality parameters cultivated in-soil and soilless hydroponic system in a plastic tunnel. It was found that soilless hydroponic system improves the quality, total and marketable yield compared with the in-soil cultivation system. For the cultivars tested, Miramar followed by FA593 were the most promising under soilless cultivation. On the other study, Thipe et al. (2014) reported that cultivars of Bona, Star 9037, Star 9009 and Zeal grown in the same tunnel and with similar methods were significantly different in firmness, total soluble solids, pH and yield. These results suggested that assimilation and partitioning of photosynthesis products and nutrients in plants depends on the type of cultivar and its genetic make-up which in turn imply the need of more agronomic trials to evaluate the best performing cultivars for the specific environment and the need of each grower.

Table 1: South African leading tomato cultivars used for different purposes.

Fresh market	**Processing**	**Saladettes**	**Special**
Star 9010, 9011	HTX14	Cordoba	Tinker
Star 9037	Legato	Star 9082	Josephine
Staffie	Domingo	Picasso	Rosa
Candela	Kamatla	Galilea	

Celaya Pamela

Topacio

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http://tgc.ifas.ufl.edu/2016/South%20Africa%20update%20(Keith).pdf. Accessed on 28 January 2019

2.4.2 Time of transplanting

Direct seeding of tomato is not commonly used in South Africa, most farmers propagate from transplants (Maboko et al., 2012). In most cultivars, transplanting is done 6 to 7 weeks after sowing (Niederwieser and Du Plooy, 2014). Propagating from transplants reduce the risk of poor seed germination due to unfavourable soil increased uniformity of plant growth and early harvesting (Orzolek, 1996). Most vegetables species cultivated in soil are affected by the transplanting stages in response to growth and development (Leskovar et al., 1991). The seedlings of tomato transplanted at a stage of 4 or 5 weeks old had no variation in growth and development and harvesting time compared to seedlings transplanted at 6 weeks (Leskovar et al., 1991). These results, however, differ from Maboko and Du Plooy (2014), who found that direct seeding of tomato in sawdust and seedlings transplanted at a stage of 3 - 5 weeks produce early marketable fruits and early total yields than seedlings transplanted at 6 weeks. This increase in early total yield and early marketable fruits was enhanced by the anchoring of the taproot and early development of secondary roots, thus increasing nutrients and water uptake by a plant (Leskovar and Cantliffe, 1993). Commercial seedling growers produce a large number of seedlings per unit area in a tray with small cavities to reduce the amount of growing media (Peterson et al., 1991). Thus seedlings get overcrowded and roots bound formation results in competing for light amongst one another and unable to efficiently absorb water and nutrients. Seedling transplanted after six weeks become weak and show nutrient deficiencies for a certain period due to the lag phase caused by mechanical damage on plant roots during transplanting (Maatjie, 2018).

2.4.3 Growing media

Most hydroponically produced tomato is cultivated and fertigated in a growing media rather than soil. The use of growing media improves both water and nutrients use efficiency, aeration and disease management (Sonneveld and Straver, 1994). There are several types of growing media used for tomato production in greenhouses and this includes, rock wool, perlite, coco peat, pine bark, sawdust, *etc*. The choice of the growing medium depends on the grower's consideration of cost and the effects on plant growth and development. Growing media are characterized by differences in physical and chemical properties (Papadopoulos et al., 2008). Physical characteristics of the growing media include differences in porosity, aeration, water holding capacity and gas diffusion (Michel, 2009). On the other hand, chemical properties include cation exchange capacity, pH, salinity and nutrient composition (Olympios, 1992).

Rock wool is the most popular growing media used by top commercial farmers in America and Northern Europe because of its high yield (Allaire et al., 2005). Allaire et al. (2005) found that rockwool increase the yield and fruit weight of the Tradiro tomato cultivar compared to sawdust, bark and shaving (Table3). Rock wool has a good water holding capacity and sterile (Peet and Welles, 2005). However, rock wool is very expensive and cannot be reused due to its breakable structure and high labour cost for the replacement (Straver, 1995). Szmidt et al. (1987) reported that perlite is a very good growing medium used for tomato but it is very expensive. Similarly, Hanna (2009) found that perlite increase the yield of Quest tomato cultivar compare to rock wool and pine bark (Table 2). The increase in yield on perlite is perpetuated by a good water retention capacity, good aeration and adsorption of nutrients which has a positive effect on plant growth and development (Hanna, 2010). The growing media of pine bark is a good alternative media compare to perlite especially in the Southern United States of America, where the product is prevalent and cheap (Snyder, 1994). Pine bark is less expensive, with good water retention, inert, high cation exchange capacity, good root aeration and disease-free, (Hanna, 2009). However, it cannot be reused because its structure gets destroyed when it decomposes and its frequent replacement increase the cost compare to that of perlite and time consuming (Hanna, 2009). In South Africa, sawdust is the readily available, popular product especially in KwaZulu-Natal and Mpumalanga province where larger areas are planted with commercial forest (Niederwieser and Du Plooy, 2014). Sawdust has been used with success in greenhouse tomato production and like other organic sources, it has high porosity and good water retention (Portree, 1996).

Despite that, it has been noted that there is no ideal growth medium suitable for all hydroponically grown crops. Instead, growth medium, according to Reinikainen (1992), should have a combined chemical, biological and physical requirements good for crop growth. The main challenge, however, is to identify the optimum ratio between water holding capacity and aeration (Gizas and Savvas, 2007). Maatjie et al. (2018) Investigated the influence of particle size of sawdust as a substrate on tomato yield, in a non-temperature-controlled plastic tunnel includes, fine (800 µm; F), medium (1.4 mm; M) and coarse (3.4 mm; C), and combination of particle sizes at the ratio of

50:50 (v/v), namely fine + coarse (F:C), Medium + Fine (M:F) and Medium + Coarse (M:C). The authors found that the particle size of treatment FC and F increase the marketable and total yield of tomato fruit compared with C, M, MF and MC. This was attributed to low air-filled porosity and increased water-holding capacity of FC and F and this suggested that the most suitable particle size of sawdust in an open-bag hydroponic system for tomato production is FC or F.

Table 2 the influence of growing media on tomato yield (Quest cultivar).

Growing media	Early (kg plant^{-1})	Total yield (kg)	Fruit weight (g fruit^{-1})
Perlite	2.2a	10.7a	210ab
Pine bark	1.9b	9.9b	213a
Rockwool	2.1a	9.6b	204b

Source: (Hanna, 2009)

Table 3 Growth media impact on the tomato yield of Tradiro cultivar.

Growing media	Yield (kg m^{-2} wk^{-1})	Fruit weight (g fruit^{-1})
Rockwool	1.32a	136a
Sawdust	1.01c	121b
Shavings	1.07bc	122b
Bark	1.19ab	130ab

Source: (Allaire et al,. 2005)

2.4.4 Plant population

2.4.4.1 Spacing and plants per hectare

Plant density regarded as the most important horticultural practices affecting tomato yield. Tomato plants are recommended to be planted in an area of about 1.3 m^2 with a spacing of 350 - 400 mm between the plants and 1200 mm between the rows (Snyder, 2007). Tomatoes planted in open field has different response in plant density to plants produced in greenhouse.

The yield of unheated greenhouse tomato can be increased by increasing the plant density (Saglan and Yazgan, 1995). Santos et al. (2010), found that small spacing in-row in open field-planted tomato had increased in yield. Amundson et al. (2012), revealed that spacing of 70 cm in protected cultivation increase yield per plant and had large fruit size, however, the yield per unit area was reduced. Amundson et al. (2012), also found that tomato plant spacing of 30 cm reduce number of fruits per plant and had small fruit size. However, the yield per unit area on the other hand was increased. The yield of tomato planted in greenhouses depends on the competition of photo assimilate available to the plant for photosynthesis. Wider spacing increase the amount of light received by the plants thus, resulted to increase photosynthesis, increase water and nutrients uptake (Papadopoulos and Pararajasingham, 1997). Overcrowded plants reduce the penetration of light to the plants resulting in poor photosynthesis, reduced transpiration and low water and nutrients uptake. Therefore, high plant density suggested only be used when producing tomatoes for the market that has no fruits size restriction.

2.4.4.2 Number of stem production

Indeterminate grown tomatoes are commonly produced in a pot as either single stem, double stem, or two plants per pot. In a single stem method, all suckers stem are removed and allowed to grow as one single leader stem (Fig.1). Plants propagated with a single stem method produce extra-large fruit to medium fruit, big foliage, long and big stems due to less competition of light, water and nutrients among plants (Maboko et al., 2011). Hence, tomatoes produced with this method have a low number of fruits per plant because the plant uses more energy for cell enlargement rather than producing a high number of fruit (Maboko and Du Plooy, 2009). Double stem on the other hand, achieve by planting one plant in a pot and allow the second sucker to grow as a second main stem resulting to double leader stems growing (Fig. 2) (Snyder, 2007). Tomato plants produced in double stem increase the yield per unit area (Amundson et al., 2012). Borisoy et al. (1978) reported that tomato plants cultivated in a double stem method in greenhouse increase the yield per unit area from 10% to 15%. This increase in tomato yield per unit area is caused by allowing the second sucker to grow as the second stem which increases the number of trusses bearing on the tomato plant increasing the number of fruit per plant (Maboko and Du Plooy, 2009). An increase in yield in the double stem is also caused by an optimal leaf area index (LAI) which increases the light penetrating in the plants which promotes pollination. The single stem method and two plants per pot have high LAI which increases stigma exertion caused by high moisture content due to low air circulation and light penetration inside the greenhouse (Gorguet et al., 2008). Amundson et al. (2012) reported that double stem pruning had the highest number of marketed fruit than a single stem method. This increase in marketed fruits is caused by a slight competition that occurs among the stems, which is beneficiary since photo assimilates, water and nutrients are supplied to two stems more efficiently. Therefore, plants tend to produce medium to small fruit size and are less prone to cracking.

Planting two plants in one pot (Fig. 3) is a commonly used method by many farmers trying to optimize their yield since the tunnel has limited planting space and high production cost. Planting two plants in one pot increases yield per unit area compared to a single plant growing as a single stem and double stem (Maboko and Plooy, 2008). Amundson et al. (2012), found that planting two plants per pot produced a yield of 8 kg while the double stem method in one pot produced 7 kg. From a profit point of view, planting two plants has no impact on increasing profit but it increases the cost of seedling, labour and fertigation.

Fig. 1: Single stem propagation of tomato grown in a protected environment. In this method, all suckers stem are removed and allowed to grow as one single leader stem

(Source:https://www.google.co.za/search?q=pruning+tomato+plant+to+double) Accessed on 29 January 2019.

Fig. 2: Double stem propagation of tomato cultivar grown in the controlled environment. The sucker stem at the bottom can be allowed to grow as the second main stem to form double leader stems growing.

(Source : https://www.google.co.za/search?q=pruning+tomato+plant+to+double). Access on 29 January 2019

Fig. 3: Two plants per pots of tomato propagated in the greenhouse. All sucker stems in this method can be pruned to grow as a single stem.

2.4.5 Water requirements

Irrigation is an essential component influence the yield and quality of greenhouse produced tomato (May and Gonzales, 1993). The tomato plant has a specific water requirement per day which needs to be properly managed to optimize yield. Drip irrigation is one of the most commonly used methods in greenhouse production and it is known as a good water-saving method and it increases yield and fruit quality while on the other hand reducing the chances of disease infestation. Over irrigation or under irrigation have a negative impact on plant growth and fruit quality. Salokhe et al. (2005) reported that water consumption of different tomato cultivars, which includes Rambo, Daniela and Moneymaker, ranges from 0.19 to 1.03 L per plant per day at different water salinity. On the other study, Tiwari et al. (2000), found that tomato plant requires water ranges from 0.89 to 2.3 L per plant per day. Snyder (1992), reported that a new transplant needs only 0.05 L of water per day while a mature plant on a sunny day needs about 2.7 L per day. Generally, a fully grown tomato plant needs 1.8 L per day (Snyder, 1992).

2.4.5.1 Irrigation effects on yield and total soluble solids

Increasing the rate of irrigation on tomato increases the yield of the total crop. High water content received by the plant increases the uptake of nutrients and photosynthesis increasing tomato growth and development. However, high water transportation by xylem to plants parts increases the osmosis of water within the fruits, thus increasing the turgor pressure of the fruit and become very prone to cracking since the fruit cuticle is very thin. Undersupply of water reduce the growth rate of the plant and yield because water stress reduces the photosynthesis rate and assimilation of plant nutrients (Shinohara et al., 1994). Therefore, a balanced watering of this vegetable crop is important to ensure the production of high quality with a prolonged shelf life.

The TSS concentration in tomato fruit is one of the most important quality attributes in the processing market (Johnstone et al., 2005). The price of tomato fruit in a processing market is determined by the amount of TSS available in a fruit (Johnstone et al., 2005). The amount of water received by the tomato plant is one of the most important attributes determining the TSS available in the fruit (Patanè and Cosentino, 2010). TSS in a tomato fruit can be increased by reducing the amount of water supplied to the plant (Pulupol et al., 1996). However, reducing the amount of water received by the plant reduces the total yield of the plant (May and Gonzales, 1998). Tüzel et al. (1993) reported similar results on the yield of tomato produced under deficit irrigation. Patanè et al. (2011) suggested that 50% irrigation water could improve TSS and yield of tomato. Maboko (2007) found that 50% of water stress in cherry tomatoes increased fruit quality attributes including TSS, titratable acidity, vitamin C, and total sugars but reduced the total yield. On the other hand, Cahn et al. (2001) reported that irrigation cutoff at the onset of fruit ripening increased both TSS and yield. The findings reported by Cahn et al. (2001) are not possible for indeterminate tomato since they produce fruit continuously. Therefore, the current findings reported by the researchers necessitates more research on cultural practices that could improve TSS without reducing the total yield.

2.4.5.2 Fertilizer and nutrient requirements

The uptake of nutrients and their transportation is heavily affected by adsorption in the root system. Some ions in the nutrient solution are taken up in large quantities than others because ion uptake depends on the plant species, cultivars and environmental conditions (Marschner, 1995). In most cases, plants are facing the difficulties in obtaining a sufficient supply of nutrients to satisfy the demand for cellular processes due to the relative immobility of fertilizers. Plants absorb nutrients from the root zone solution and must be dissolved to be mobile (Barber, 1995). The nutrients essential for plant growth and development are classified as macro and micronutrients. Macronutrients are the building blocks of vital cellular components required in large quantities (Shukla et al., 2014). Macronutrients essential for tomato production are nitrogen, phosphorus, magnesium, potassium, calcium, and Sulphur (Sainju et al., 2003). Oxygen, Carbon and hydrogen are also regarded as macronutrients since they are required in large quantities to build larger organic molecules of the cells (Shukla et al., 2014). However, they are regarded as a non-mineral class of macronutrients (Shukla et al., 2014). Micronutrients are required in small quantities and this includes iron, zinc, copper, manganese, molybdenum and boron (Wang et al., 2006). These micronutrients in the tomato plant are functioning as cofactors for enzyme activity (Hänsch and Mendel, 2009). A nutrient required by the crop depends on the stage of plant growth, whether vegetative or reproductive growth (Wang et al., 2006); (Table 1). K, Ca and N are required in large quantities than others to promote shoots, flower and fruit formation and improve quality (Table 1). Fertilizer application rate tends to increase with an increase in plant growth (Jones, 2007). For example, fertilizer application from transplant up to 4^{th} cluster is constant but as it reaches 5^{th} to 6^{th} cluster it increases to satisfy the need of the developing shoots and fruits (Table 1). Therefore, a proper understanding of fertilizer mixing and concentration is very crucial to promote growth and development of the plant.

Table 4: Nutrients requirements of tomato produce in hydroponic

Type of fertilizer	Transplant–4th flower	4th-6th flower	6th-maturity
Nitrogen	70 - 90 ppm	90 - 110ppm	110 - 125 ppm
Phosphorus	24 ppm	40 ppm	48 ppm
Potasium	150 - 200 ppm	200 - 250 ppm	250 - 300 ppm
Calcium	90 - 100 ppm	100 - 150 ppm	150 - 175 ppm
Magnesium	25 ppm	40 ppm	50 ppm
Iron	1.50 ppm	2,50 ppm	3 ppm
Manganese	1 ppm	2 ppm	2 ppm
Boron	0.50 ppm	1 ppm	1 ppm
Zinc	0.20 ppm	0.40 ppm	0.40 ppm
Copper	0.10 ppm	0.20 ppm	0.20 ppm
Molybdenum	0.10 ppm	0.10 ppm	0.10 ppm

Source: (Jones, 2007)

The absolute amount of fertilizer concentration does not determine the nutrient uptake by the plant but it depends on the mutual ratio of the nutrients and the conditions of the environmental (Fulton, 2011). Increasing fertilizer application while keeping the same ratio of nutrients has a small effect on the uptake of nutrients by the tomato plant (Sonneveld and Welles, 2004). Mutual ratios of cations K, Mg, Ca and Na influence yield and quality of tomato. Increasing the rate of K and Ca in nutrients solution increases the yield and quality of tomato (Muro E et al., 2008). Potassium maintains the balance of ion uptake and water, enzyme activation, promotes the flower and fruit formation and reduces physiological disorders (Upendra et al., 2003). On the other hand, calcium increases cell wall formation and reduces the chances of blossom end rot in tomato fruit (Upendra et al., 2003). Adams (1994) reported that high application of K, Na and Mg decreases the uptake of Ca resulting in to increase in blossom end rot (BER). Sonneveld and Welles (2004) reported that the recommended mutual ratio for many crops of K: Ca: Mg is 1:2:1. However, Fanasca et al. (2006) found that K 0.48, Ca 0.38 and Mg 0.14 is the most appropriate ratio as it increased the yield of tomato.

Nitrogen can be absorb by the plants in the form of nitrate (NO_3^-) or ammonium (NH_4^+). Application of NH_4^+ more than optimal is a detriment on tomato plant development and yield (Takács and Técsi, 1992). Jung et al. (1994) found that the application of NH_4^+ not exceeding 30% has no negative impact on tomato plant development and yield. Similarly, Claussen (2002) found that a tomato increase in yield with NO_3^-: NH_4^+ ratio of 75:25. Marcelis and Ho (1999); Sonneveld and Voogt (2009) reported that NH_4^+ exceeds 10 % increase the chances of BER on tomato fruit. BER incident was enhanced by the reduction of Ca uptake during the high concentration of NH_4^+. Application of NH_4^+ in small quantity increase the uptake of NO_3^- (Tabatabaei et al., 2008). A high concentration of NH_4^+ in a nutrients solution decreases the pH, thus reduces the uptake of NO_3^- since its only uptake by tomato plant under a pH ranges from 5 to 6.5. Hormone cytokinin is mostly involved in nitrogen nutrition (Zhang and Forde. 2000; Sakakibara et al., 2006; Sakakibara. 2003; Wang and Below. 1996). Cytokinin is synthesized in the root tip and is regarded as the root to shoot signal in the presence of nitrogen to promote leaf growth (Takei et al., 2002; Rahayu et al., 2005). Cytokinin promotes leaf growth in the presence of NO_3^- (Rahayu et al., 2005). Lu et al. (2009) reported that cytokinin decrease to low level during the replacement of NO_3^- by NH_4^+. This presented the evidence that high concentration of ammonium received by the plant inhibit the uptake of nitrate which play an essential role in plant growth.

2.4.6 Growth medium electrolyte conductivity (EC) effects on tomato production

Most consumers in the Southern Africa market prefer big tomato fruit with good appearance and quality. Substantial increase and decrease of growth medium electrical conductivity (EC) affect the rate of fruit growth and quality in tomatoes (Maggio et al., 2004). High EC decreases the absorption and transportation of water in the plant which results in the reduction of water flow into the fruit and reduces fruit expansion (Johnson et al., 1992). Hence, these reductions are caused by high salt stress which results in the decrease of the permeability of the roots and the xylem becomes more resistant to the transportation of water.

During the process of photosynthesis, dry matter accumulation and partitioning are negatively influenced by high EC. High EC reduces the absorption of water resulting in the decrease of stomatal conductance and an influx of CO_2. A decrease in CO_2 during photosynthesis decreases the synthesis of sugars resulting in negative effects on plant growth and fruit development. Reduction of water supply and high EC reduces the fruit strength (Dorai et al., 2001). Tomato is produced at an optimal EC of 2mS.cm^{-1} up to 2.5 mS.cm^{-1} (Sonneveld and Voogt, 2009). Sonneveld and Welles (1988) reported that an increase of every 1 mS.cm^{-1} after reaching 2.5 mS.cm^{-1} reduced the yield of tomato by 5 to 7%. Dorai et al. (2001) reported that an EC of 10

$mS.cm^{-1}$ reduce plant dry weight by (19%) compare to EC of 2 $mS.cm^{-1}$ but do not affect dry matter partitioning. Ehret and Ho (1986) reported that an EC of 17 $mS.cm^{-1}$ increases the accumulation of sugars in tomato fruit but reduces yield. These results, therefore, suggest that as the EC increases on plant roots, the absorption of water decreases which results in a decrease in plant growth and fruit size and low yield. On the other hand, Adams (1989); Dorais et al. (2000); Hobson (1988) reported that soluble solids, titratable acids, fructose, glucose, minerals, volatile compounds, carotene and vitamin C increases with an increase in EC. Since tomato produced under high EC accumulate high antioxidants, this means that tomato produced in this way may be used as a strategy to reduce the chances of getting cancer and other diseases.

The postharvest quality and shelf-life of tomato fruit depend on pre-harvest factors. Several studies reported that tomato fruit shelf life increases with an increase in growth medium EC. Tomato fruit produce under high EC (more than 2.5 $mS.cm^{-1}$) has thick cuticle and less prone to fruit cracking because of reducing fruit turgor pressure (Li et al., 1999). However, tomato fruits produced under high EC are susceptible to blossom end rot (BER) because of the high import of assimilates and insufficient supply of calcium caused by poor development of xylem within the fruits (Adams, 1992; Belda and Ho, 1993; Belda et al., 1996).

2.4.7 pH

The pH measures the concentration of hydrogen ions in the solution. The pH less than 7 is acidic if more than 7 is alkaline while on the other hand when it is 7 is neutral (Trejo-Téllez and Gómez-Merino, 2012). The pH range of nutrient solution for greenhouse tomato is between 5.6 and 5.8.

High pH in a nutrient solution may cause precipitation of some nutrients and form insoluble salts (Havlin et al., 2005). Tomato plants produced at a pH of more than 6 show the deficiency of phosphorus, iron, manganese and zinc because they become insoluble (Bar-Yosef, 2008). Conversely, the cation Na^{+} K^{+}, Ca^{2+}, Mg^{2+} may leach out in a media with a pH of less than 5 (Jones and Jacobsen, 2005). Differences in the uptake of cation and anion have a large impact on pH in a roots zone. The uptake of more cation by plants causes the increase of anion in a root zone while more uptake of anion by plants results in an increase of cation in the root zone. During vegetative growth, plants uptake more nitrates which results in an increase in the alkaline condition in a roots zone or drained solution. Therefore, an element such as phosphorus becomes unavailable for uptake by a plant (Adams, 2002). During flower and fruit formation, plants absorb a high concentration of potassium which leads to an increase of acid in a root zone (Adams, 2002).

2.5 Other cultivation practices

2.5.1 Pruning

Pruning is the removal of some plant parts such as leaves and suckers to reduce vegetative growth and promote reproductive growth (Jett, 2004a). Pruning in tomato is mostly practiced in indeterminate tomatoes where the plant has a long growing period and ability to produce a high yield. Removing side shoots manipulates the competition between source and sink to increase the yield and improve fruit quality (Alam et al., 2016). Maboko and Plooy (2008) reported that allowing the side shoot to grow reduces the size of tomato fruit because the nutrients and photons accumulated by plants are used by side shoots instead of the fruit. Pruning of leaves in tomato plants is necessary when the plants are overcrowded to maximize the light interception, accelerate fruit ripening, expose truss for easier harvest and reduce the chances of disease development (Heuvelink et al., 2004).

Intensive pruning of leaves may reduce the amount of light radiation resulting in a decrease in photosynthesis efficiency and carbohydrates partitioning (Li et al., 2003). Reducing leaf area index in summer may increase the vapour pressure deficit (VPD) and reduce the relative humidity (RH) within the canopy of the tomato plant and the whole greenhouse (Leonardi et al., 2000a). An increase in VPD and severe reduction in RH had a negative effect on the growth and quality of tomatoes (Leonardi et al., 2000b). Starck (1983) reported that tomato plants require partial pruning to prevent fruit from being exposed to adverse environmental conditions while the remaining leaves continue with optimal the photosynthesis process. In the study reported by Sharma and Singh (2006)), the authors demonstrated that pruning mango tree increased air temperature within the leaf canopy and decreased relative humidity than unpruned mango. A high leaf area index has a cooling effect on the plant due to the evaporative cooling effect of transpiration on the interior air temperature (Impron et al., 2008).

2.5.2 Trellising and training

Trellising plants is a common cultural practice adopted by many farmers to support a tomato stem since it is herbaceous crop. This is achieved by using a sturdy material to keep the plants off the ground, allow good penetration of light, increase usable space, increase yield and reduce diseases (Alam et al., 2016). However, it is laborious, costly and time-consuming.

Tunnel produced tomato can be trellised through either vertical or layering trellising. The selection of the trellising method is based on the type of growing structure. The vertical trellising method is achieved by securing a tomato plant with a plastic twine and hang on a horizontal wire running at a height of ± 2 m above the ground and trellis plant in a vertical direction (Fig. 4). Although there is no published work on trellising methods but communication with farmers has indicated that vertical trellising is efficient for commercial tunnels with high roofs and systems to filter solar radiation. Using vertical trellising in dome shape tunnel reduces yield because tomato grows well until they reach the height of 2m then after, the epical meristems are burn by the heat of the roof plastic since they already reached the maximum level of the greenhouse.

The layering trellising method commonly used method in the dome shape tunnel where the vertical trellising method has height limitations (http://www.commercial-hydroponic-farming.com/trellising-tomato-plants, accessed: 30 January 2019). Layering trellising method, achieved by securing tomato plants with a plastic twine and hung on a horizontal wire running at a height of ±2 m above the ground and trellis in a diagonal direction (Fig. 5). When plant height is close to the overhead wire, the twine and plant are moved side sway down the horizontal wire. With this method, plants grow until limited by lifecycle or diseases. Although there are no studies on this trellising method, it is believed that tomatoes produced with the layering trellising method have a higher yield compared to the vertical trellising method since there is no height limitation.

However, there are cases where farmers use this layering trellising method, keeping the plant growing for a longer period but still do not achieve potential yields. This is hypothesized to be linked to the timing of trellising because most farmers allow the plant to grow vertical until they reach the maximum level of the tunnel and late applying layering trellising. Late layering trellising of the tomato plant changes the orientation of the plant that might also affect the orientation of the vascular system. Harrison and Pickard (1984) reported that changing the plant growing position might cause the settling of amyloplasts against the cell vacuole resulting in the deformation of the tonoplast (Harrison and Pickard, 1984). If the enzyme 1-aminocylopropane-1-carboxylic acid (ACC) is situated in the tonoplast, such deformation might increase its ability to release ethylene from ACC in the vacuole (Harrison and Pickard, 1984). An increase of ethylene in the vacuole retards stem elongation, increases respiration and decreasing photosynthesis (Jaffe and Telewski, 1984). This mechanical stress during critical reproductive stages of the plant might also change carbohydrates partitioning patterns leading to reduced yields. In addition to various growths, morphological, anatomical, physiological and metabolic changes, hormonal balance is also disturbed by mechanical stress (Jaffe, 1979). It is, therefore, important that the layering trellising method is applied during stages that will cause minimal disturbance to the plant production system.

Fig.4: Tomato crops in a vertical trellising method in dome shape tunnel.

Fig. 5: Tomato crops in layering trellising method in dome shape tunnel.

2.6 Conclusion and prospects

The importance of high yield and good quality in tomato production has grown regularly in the past decade due to high demand and competitive pressure triggered by the increase in health concerns. As a result, quality has become the most important factor in a customer decision to purchase. The quality in tomato fruits is measured based on firmness, fruit size, total soluble solids

(TSS) and defects free. However, in most studies research has demonstrated that tomato plants with high TSS had low yield while tomato plants with high yield had low TSS. Various cultural and management practices contribute to TSS and many studies have not singled out the cultural practice that increases yield while at the same time also increasing TSS. Therefore, more studies are needed to investigate the cultural practices that increase yield and TSS concurrently. The present literature review has shown that the trellising of tomato plants has an effect on yield and quality of tomato fruits, however, there is no sufficient scientific evidence to support which trellising method has a positive effect on tomato yield and quality produced in protected structure. Therefore, more research is needed to identify the trellising method that can have a positive effect on tomato crops to attain it is yield production potential. In addition, the yield and quality of tomato production are primarily depended on horticultural practices used to produce. The current literature review demonstrated that cultivars, growing media, transplanting, plant density, watering, and fertigation have a significant influence on the tomato plant to produce it is yield potential. A proper understanding of the responses of plants to particular horticultural practices could increase the yield and quality of tomato, suppress poverty, malnutrition and increase the food security of a growing population.

2.7 References

http://www.johnnyseeds.com/trellising. Last accessed: 30 January2019

http://tgc.ifas.ufl.edu/2016/South%20Africa%20update%20(Keith).pdf. Last accessed: 28 January 2019

Source:https://www.google.co.za/search?q=pruning+tomato+plant+to+double+stem&rlz. Last accessed : 29 January 2019

http://www.commercial-hydroponic-farming.com/trellising-tomato-plants. Last accessed: 30 January 2019

Adams, P. 2002. Nutritional control in hydroponics. Hydroponic production of vegetables and ornamenta. Japanese Journal of Tropical Agriculture, 49, 45-52.

Agcenter, L. 2009. Louisiana Summary–Agriculture & Natural Resources 2008. Louisiana State University Agricultural Center. Baton Rouge, LA**,** 16.

Alam, M., Islam, N., Ahmad, S., Hossen, M. & Islam, M. 2016. Effect of different staking methods and stem pruning on yield and quality of summer tomato. Bangladesh Journal of Agricultural Research, 41**,** 419-432.

Allaire, S.E., Caron, J., Ménard, C. & Dorais, M. 2005. Potential replacements for rockwool as growing substrate for greenhouse tomato. Canadian Journal of Soil Science, 85**,** 67-74.

Amundson, S., Deyton, D.E., Kopsell, D.A., Hitch, W., Moore, A. & Sams, C.E. 2012. Optimizing plant density and production systems to maximize yield of greenhouse-grown ‘Trust’Tomatoes. Horticultural Technology, 22**,** 44-48.

Argade, M., Kadam, J., Garande, V., Patgaonkar, D., Patil, V. & Sonawane, P. 2018. Effect of different shading intensities on growth and yield of cherry tomato. Journal of Applied and Natural Science, 10, 352-357.

Arin, L. & Ankara, S. 2001. Effect of low-tunnel, mulch and pruning on the yield and earliness of tomato in unheated glasshouse. Journal of Applied Horticulture, 3, 23-27.

Bar-Yosef, B. 2008. Fertigation management and crops response to solution recycling in semi-closed greenhouses. Elsevier: Amsterdam, The Netherlands. San Diego: Academic Press, p. 341-424.

Barber, S.A. 1995. Soil nutrient bioavailability: a mechanistic approach, John Wiley & Sons, p. 1-5.

Brandt, S., Pék, Z., Barna, É., Lugasi, A. & Helyes, L. 2006. Lycopene content and colour of ripening tomatoes as affected by environmental conditions. Journal of the Science of Food and Agriculture, 86, 568-572.

Cahn, M., Herrero, E., Snyder, R. & Hanson, B. 2001. Water management strategies for improving fruit quality of drip-irrigated processing tomatoes. Plant and Soil, 247, 199-209.

Dorai, M., Papadopoulos, A. & Gosselin, A. 2001. Influence of electric conductivity management on greenhouse tomato yield and fruit quality. Agronomie, 21, 367-383.

Du Plooy, C., Maboko, M., Van Den Heever, E. & Chiloane, S. 2012. Research and technology transfer by the Agricultural Research Council to sustain the South African hydroponic industry. Acta Horticulturae, 947, 147-152.

Ehret, D.L. & Ho, L.C. 1986. Effects of osmotic potential in nutrient solution on diurnal growth of tomato fruit. Journal of Experimental Botany, 37, 1294-1302.

Fanasca, S., Colla, G., Maiani, G., Venneria, E., Rouphael, Y., Azzini, E. & Saccardo, F. 2006. Changes in antioxidant content of tomato fruits in response to cultivar and nutrient solution composition. Journal of Agricultural and Food Chemistry, 54**,** 4319-4325.

FAO. 2014. Food and Agriculture Organization (FAO) of the United Nations. Production quantities of tomato in the world. http://www.fao.org/faostat/en/#data/QC/visualize. Last accessed 20 september 2018

Ganesan, M., Rajesh, M., Solairaj, P. & Senthilkumar, T. 2012. Tomato as A Pioneer in Health Management. International Journal of Pharmaceutical, Chemical and Biological Science, 2**,** 210-217.

Giacomelli, G.A. & Roberts, W.J. 1993. Greenhouse covering systems. Horticultural Technology, 3**,** 50-58.

Gizas, G. & Savvas, D. 2007. Particle size and hydraulic properties of pumice affect growth and yield of greenhouse crops in soilless culture. Horticulture Science, 42**,** 1274-1280.

Gorguet, B., Eggink, P. M., Ocana, J., Tiwari, A., Schipper, D., Finkers, R., Visser, R. G. & Van Heusden, A. W. 2008. Mapping and characterization of novel parthenocarpy QTLs in tomato. Theoretical and Applied Genetics, 116**,** 755-767.

Hanna, H.Y. 2009. Influence of cultivar, growing media, and cluster pruning on greenhouse tomato yield and fruit quality. Horticultural Technology, 19**,** 395-399.

Hanna, H.Y. 2010. Reducing Time and Expense to Recycle Perlite for Repeat Use in Greenhouse Tomato Operations. Horticultural Technology, 20**,** 746-750.

Hänsch, R. & Mendel, R.R. 2009. Physiological functions of mineral micronutrients (Cu, Zn, Mn, Fe, Ni, Mo, B, Cl). Current Opinion in Plant Biology, 12**,** 259-266.

Harrison, M. & Pickard, B.G. 1984. Burst of ethylene upon horizontal placement of tomato seedlings. Plant Physiology, 75, 1167-1169.

Havlin, J.L., Beaton, J.D., Tisdale, S.L. & Nelson, W.L. 2005. Soil fertility and fertilizers: An introduction to nutrient management, Pearson Prentice Hall Upper Saddle River, NJ, p.159

Heuvelink, E. 2005. Tomatoes, CABI, p. 60-95

Heuvelink, E., Bakker, M., Elings, A., Kaarsemaker, R. & Marcelis, L. 2004. Effect of leaf area on tomato yield. Acta Horticulturae, 691, 43-50.

Ilić, Z. S., Milenković, L., Šunić, L. & Fallik, E. 2015. Effect of coloured shade-nets on plant leaf parameters and tomato fruit quality. Journal of the Science of Food and Agriculture, 95, 2660-2667.

Impron, I., Hemming, S. & Bot, G. 2008. Effects of cover properties, ventilation rate, and crop leaf area on tropical greenhouse climate. Biosystems Engineering, 99, 553-564.

Jaffe, M. 1979. Thigmomorphogenesis: the effect of mechanical perturbation on the growth of plants, with special reference to anatomical changes, the role of ethylene, and interaction with other environmental stresses. Stress physiology in crop plants, CiNii, p.25-59.

Jaffe, M.J. & Telewski, F.W. 1984. Thigmomorphogenesis: callose and ethylene in the hardening of mechanically stressed plants. Phytochemical adaptations to stress. Springer, p.79-95.

Jensen, M.H. 2001. Controlled Environment agriculture in deserts, tropics and temperate regions-A World Review. International Symposium on Design and Environmental Control of Tropical and Subtropical Greenhouses 578, 19-25.

Jett, L.W. 2004a. High tunnel tomato production. Department of Agriculture: University of Missouri.

Jett, L.W. 2004b. Production of tomatoes within a high tunnel. Department of Agriculture: University of Missouri.

Johnson, R., Dixon, M. & Lee, D. 1992. Water relations of the tomato during fruit growth. Plant, Cell & Environment, 15**,** 947-953.

Johnstone, P., Hartz, T., Lestrange, M., Nunez, J. & Miyao, E. 2005. Managing fruit soluble solids with late-season deficit irrigation in drip-irrigated processing tomato production. Horticultural Science, 40**,** 1857-1861.

Jones, C. & Jacobsen, J. 2005. Plant Nutrition and Soil Fertility. CRC press, p. 15-25.

Jones Jr, J.B. 2007. Tomato plant culture: in the field, greenhouse, and home garden, CRC press, p. 179-202.

Lamont, W.J. 2009. Overview of the use of high tunnels worldwide. Horticultural Technology, 19**,** 25-29.

Lamont, W.J., Mcgann, M.R., Orzolek, M.D., Mbugua, N., Dye, B. & Reese, D. 2002. Design and construction of the Penn State high tunnel. Horticultural Technology, 12**,** 447-453.

Leonardi, C., Guichard, S. & Bertin, N. 2000a. High vapour pressure deficit influences growth, transpiration and quality of tomato fruits. Scientia Horticulturae, 84**,** 285-296.

Leonardi, C., Guichard, S. & Bertin, N. 2000b. High vapour pressure deficit influences growth, transpiration and quality of tomato fruits. Scientia Horticulturae, 84**,** 285-296.

Leskovar, D.I. & Cantliffe, D.J. 1993. Comparison of plant establishment method, transplant, or direct seeding on growth and yield of bell pepper. Journal of the American Society for Horticultural Science, 118**,** 17-22.

Leskovar, D.I., Cantliffe, D.J. & Stoffella, P.J. 1991. Growth and yield of tomato plants in response to age of transplants. Journal of the American Society for Horticultural Science, 116**,** 416-420.

Li, H.Y., Chang, C.S., Lu, L.S., Liu, C.A., Chan, M.T. & Charng, Y.Y. 2003. Over-expression of Arabidopsis thaliana heat shock factor gene (*AtHsfA1b*) enhances chilling tolerance in transgenic tomato. Botanical Bulletin of Academia Sinica, 44, 129-140

Li, J.H., Sagi, M., Gale, J., Volokita, M. & Novoplansky, A. 1999. Response of tomato plants to saline water as affected by carbon dioxide supplementation. I. Growth, yield and fruit quality. The Journal of Horticultural Science and Biotechnology, 74**,** 232-237.

Lopez, D., Carazo, N., Rodrigo, M. & Garcia, J. 2006. Coloured shade nets effects on tomato crops quality. Acta Horticulturae, 747, 121-124.

Lu, Y.L., Xu, Y.C., Shen, Q.R. & Dong, C.X. 2009. Effects of different nitrogen forms on the growth and cytokinin content in xylem sap of tomato (*Lycopersicon esculentum Mill*) seedlings. Plant and Soil, 315**,** 67.

Maatjie, M.A., Maboko, M.M. & Modise, D.M. 2018. Yield of hydroponically grown tomato (*Solanum lycopersicon*) as affected by different particle sizes of sawdust. South African Journal of Plant and Soil**,** 35**,** 1-3.

Maboko, M. & Du Plooy, C.P. 2009 Effect of stem and fruit pruning on yield and quality of hydroponically grown tomato. African Crop Science Conference Proceeding, 9, 27-29.

Maboko, M., Du Plooy, C.P. & Bertling, I. 2010. Performance of tomato cultivars in temperature and non-temperature controlled plastic tunnels. Acta Horticulturae, 927, 405-411.

Maboko, M., Du Plooy, C.P. & Chiloane, S. 2011. Effect of plant population, fruit and stem pruning on yield and quality of hydroponically grown tomato. African Journal of Agricultural Research, 6, 5144-5148.

Maboko, M., Du Plooy, C.P. & Chiloane, S. 2012. Effect of plant population, stem and flower pruning on hydroponically grown sweet pepper in a shadenet structure. African Journal of Agricultural Research, 7, 1742-1748.

Maboko, M. & DU Plooy, C.P. 2008. Effect of pruning on yield and quality of hydroponically grown cherry tomato (*Lycopersicon esculentum*). South African Journal of Plant and Soil, 25, 178-181.

Maboko, M. M. 2007. Growth, yield and quality of tomatoes (Lycopersicon Esculentum Mill.) and lettuce (*Lactuca Sativa L.*) as affected by gel-polymer soil amendment and irrigation management, South Africa, MSc Horticulture, University of Pretoria

Maboko, M. M. & Du Plooy, C. P. 2014. Yield of two hydroponically grown tomato cultivars as affected by transplanting stage or direct seeding. Horticutural Science, 49, 438-440.

Maggio, A., De Pascale, S., Angelino, G., Ruggiero, C. & Barbieri, G. 2004. Physiological response of tomato to saline irrigation in long-term salinized soils. European Journal of Agronomy, 21, 149-159.

Marcelis, L. & Ho, L. 1999. Blossom-end rot in relation to growth rate and calcium content in fruits of sweet pepper (*Capsicum annuum L.*). Journal of Experimental Botany, 50, 357-363.

Marschner, H. 1995. Functions of Mineral Nutrients-8: Macronutrients. Soil Science and Plant Nutrition 52, 387-393.

May, D. & Gonzales, J. 1993. Irrigation and nitrogen management as they affect fruit quality and yield of processing tomatoes. Acta Horticulturae, 376, 227-234.

May, D. & Gonzales, J. 1998. Major California processing tomato cultivars respond differently in yield and fruit quality to various levels of moisture stress. Acta Horticulturae, 487, 525-530.

Michel, J.C. 2009. Influence of clay addition on physical properties and wettability of peat-growing media. Horticultural Science, 44**,** 1694-1697.

Muro E.J., Sánchez G,P. & Ramírez S,L. 2008. Potassium affects the lycopene and ß-carotene concentration in greenhouse tomato. International Symposium on Tomato in the Tropics. Acta Horticulturae, 821, 223-228.

Nangare, D., Singh, J., Meena, V., Bhushan, B. & Bhatnagar, P. 2015. Effect of green shade nets on yield and quality of tomato (*Lycopersicon esculentum Mill*) in semi-arid region of Punjab. Asian Journal of Advances in Basic and Applied Science, 1**,** 1-8.

Niederwieser, J. & Du Plooy, C. 2014. Guide to hydroponic vegetable production in South Africa. Agricultural Research Council, Roodeplaat Vegetable and Ornamental Plants Institute, Pretoria, South Africa.

Olympios, C. 1992. Soilless media under protected cultivation rockwool, peat, perlite and other substrates. Acta Horticulturae, 323, 215-234.

Orzolek, M.D. 1996. Stand establishment in plasticulture systems. Horticultural Technology, 6**,** 181-185.

Papadopoulos, A. & Pararajasingham, S. 1997. The influence of plant spacing on light interception and use in greenhouse tomato (*Lycopersicon esculentum Mill.*): A review. Scientia Horticulturae, 69**,** 1-29.

Patanè, C. & Cosentino, S. 2010. Effects of soil water deficit on yield and quality of processing tomato under a Mediterranean climate. Agricultural Water Management, 97, 131-138.

Patanè, C., Tringali, S. & Sortino, O. 2011. Effects of deficit irrigation on biomass, yield, water productivity and fruit quality of processing tomato under semi-arid Mediterranean climate conditions. Scientia Horticulturae, 129, 590-596.

Patil, M. & Bhagat, A. 2014. Yield response of cucumber (Cucumis sativus L.) to shading percentage of shade net. International Journal of Agricultural Engineering, 7, 243-248.

Peet, M. & Welles, G. 2005. Greenhouse tomato production. CABI, p. 257-302.

Peterson, T.A., Reinsel, M.D. & Krizek, D.T. 1991. Tomato (*Lycopersicon esculentum Mill*., cv.'Better Bush') plant response to root restriction. Journal of Botany, 42, 1241-1249.

Portree, J. 1996. Greenhouse vegetable production guide. Ministry of agriculture, fisheries and food. Victoria, BC, Canada.

Priya, N., Vijayakumar, M., Veeraragavathatham, D., Jeyakumar, P. & Chezhiyan, N. 2002. Effect of seasons and growth environments on paprika (*Capsicum annuum* var. longum) growth and yield. South Indian Horticulture, 50, 463-471.

Pulupol, L.U., Behboudian, M.H. & Fisher, K.J. 1996. Growth, yield, and postharvest attributes of glasshouse tomatoes produced under deficit irrigation. Horticultural Science, 31, 926-929.

Quaglitto, L. 1976. The effects of shading on sweet peppers. Informatore Agrario, 32, 22517-22518.

Rahayu, Y.S., Walch-Liu, P., Neumann, G., Römheld, V., Von Wirén, N. & Bangerth, F. 2005. Root-derived cytokinins as long-distance signals for NO3−-induced stimulation of leaf growth. Botany, 56, 1143-1152.

Reeder, B. 2006. High Tunnel Production of Tomatoes and Snapdragons for Season Extension in Southeastern Alabama. Southeastern Alabama. MSC Horticulture. Auburn University

Reinikainen, O. 1992. Choice of growing media for pot plants. Acta Horticulturae, 342, 357-360.

Resh, H. 2017. Hydroponics: Questions & Answers for Successful Growing, Routledge, p. 43-54

Resh, H.M. 2016. Hydroponic food production: a definitive guidebook for the advanced home gardener and the commercial hydroponic grower, CRC Press, p. 9-29

Rodríguez-Delfín, A. 2011. Advances of hydroponics in Latin America. Acta Horticulturae, 947, 23-32.

Saglan, N. & Yazgan, A. 1995. The effects of planting density and the number of trusses per plant on earliness, yield and quality of tomato grown under unheated high plastic tunnel. Acta Horticulturae, 412, 258-267.

Sainju, U.M., Dris, R. & Singh, B. 2003. Mineral nutrition of tomato. Food, Agriculture & Environment, 1**,** 176-183.

Sakakibara, H. 2003. Nitrate-specific and cytokinin-mediated nitrogen signaling pathways in plants. Journal of Plant Research, 116**,** 253-257.

Sakakibara, H. 2006. Cytokinins: activity, biosynthesis, and translocation. Annu. Rev. Plant Biology, 57**,** 431-449.

Salunkhe, D. & Kadam, S. 1995. Handbook of Fruit Science and Technology, CRC Press, p. 387.

Santos, B.M., Scott, J.W. & Ramírez-Sánchez, M. 2010. In-row distances and nitrogen fertilization programs for 'Tasti-Lee'specialty tomato. Horticultural Technology, 20**,** 579-584.

Shahak, Y. 2006. Photo-selective netting for improved performance of horticultural crops. A review of ornamental and vegetable studies carried out in Israel. Acta Horticulturae, 770, 161-168.

Shahak, Y., Gussakovsky, E.E., Cohen, Y., Lurie, S., Stern, R., Kfir, S., Naor, A., Atzmon, I., Doron, I. & Greenblat-Avron, Y. 2004. ColorNets: a new approach for light manipulation in fruit trees. Acta Horticulturae, 636**,** 609-616.

Sharma, R. & Singh, R. 2006. Pruning intensity modifies canopy microclimate, and influences sex ratio, malformation incidence and development of fruited panicles in 'Amrapali'mango (*Mangifera indica* L.). Scientia Horticulturae, 109**,** 118-122.

Shi, J. & Maguer, M.L. 2000. Lycopene in tomatoes: chemical and physical properties affected by food processing. Critical Reviews in Food Science and Nutrition, 40**,** 1-42.

Shinohara, Y., Akiba, K., Maruo, T. & Ito, T. 1994. Effect of water stress on the fruit yield, quality and physiological condition of tomato plants using the gravel culture. Hydroponics and Transplant Production 396**,** 211-218.

Shukla, R., Sharma, Y.K. & Shukla, A.K. 2014. Molecular mechanism of nutrient uptake in plants. International Journal of Current Research and Academic Research, 2**,** 142-154.

Snyder, R. 2007. Greenhouse tomato. Handbook. Mississippi State Ext, p.1828.

Snyder, R.G. 1992. Greenhouse tomato handbook. Publication-Cooperative Extension Service, Mississippi State University (USA), p.1–29.

Snyder, R.G. 1994. Pine bark, rice hulls, and other inexpensive media for greenhouse tomato production in the South. Horticultural Science, 29**,** 733-733.

Sonneveld, C. & Straver, N. 1994. Nutrient solutions for vegetables and flowers grown in water or substrates. Research Station for Floriculture and Glasshouse Vegetables, 8**,** 45.

Sonneveld, C. & Voogt, W. 2009. Nutrient management in substrate systems. Plant nutrition of greenhouse crops. Springer, p. 277-312

Sonneveld, C. & Welles, G. 1988. Yield and quality of rockwool-grown tomatoes as affected by variations in EC-value and climatic conditions. Plant and Soil, 111**,** 37-42.

Sonneveld, C. & Welles, G. 2004. Cation concentrations of plant tissues of fruit-vegetable crops as affected by the EC of the external nutrient solution and by humidity. Acta Horticulturae 697, 377-386.

Soria, T. & Cuartero, J. 1993. Tomato fruit yield and water consumption with salty water irrigation. Acta Horticulturae 458, 215-220.

Starck, Z. 1983. Photosynthesis and endogenous regulation of the source-sink relation in tomato plants [beta-naphthoxyacetic acid, GA, dry matter]. Photosynthetica ,17, 1-11.

Straver, W. 1995. Inert growing media for greenhouse tomatoes. Proceedings of Greenhouse Tomato Seminar. United States Press, p. 13-15

Szmidt, R., Hall, D. & Hitchon, G. 1987. Development of perlite culture systems for the production of greenhouse tomatoes. Acta Horticulturae, 221, 371-378.

Tabatabaei, S., Yusefi, M. & Hajiloo, J. 2008. Effects of shading and NO3: NH4 ratio on the yield, quality and N metabolism in strawberry. Scientia Horticulturae, 116**,** 264-272.

Takács, E. & Técsi, L. 1992. Effects of NO3-/NH4+ ratio on photosynthetic rate, nitrate reductase activity and chloroplast ultrastructure in three cultivars of red pepper (*Capsicum annuum L.*). Journal of Plant Physiology, 140**,** 298-305.

Thipe, E., Workneh, T., Odindo, A. & Laing, M. 2014. Effects of cultivars, growing and storage environments on quality of tomato. Agricultural, Food and Biotechnological Engineering, 8**,** 1269-1278.

Tinyane, P.P., Sivakumar, D. & Soundy, P. 2013. Influence of photo-selective netting on fruit quality parameters and bioactive compounds in selected tomato cultivars. Scientia Horticulturae, 161, 340-349.

Tiwari, K., Singh, A. & Mal, P. 2000. Economic feasibility of raising seedlings and vegetables production under low cost plastic tunnel. International Committee of Plastics in Agriculture (ICPA), Paris, Plasticulture on-line publication.

Trejo-Téllez, L.I. & Gómez-Merino, F.C. 2012. Nutrient solutions for hydroponic systems. InTech, p.1-23

Tüzel, Y., Ul, M. & Tüzel, I. 1993. Effects of different irrigation intervals and rates on spring season glasshouse tomato production. Agronomie, 366, 389-396.

Upendra, M., Sainju, R.D. & Singh, B. 2003. Mineral nutrition of tomato (Training Report). Thailand, p. 325-327

Van Straten, G., Van Willigenburg, G., Van Henten, E. & Van Ooteghem, R. 2010. Optimal control of greenhouse cultivation, CRC press, p. 1-21

Von Elsner, B., Briassoulis, D., Waaijenberg, D., Mistriotis, A., Von Zabeltitz, C., Gratraud, J., Russo, G. & Suay-Cortes, R. 2000. Review of structural and functional characteristics of greenhouses in European Union countries, part II: typical designs. Journal of Agricultural Engineering Research, 75, 111-126.

Wang, H., Inukai, Y. & Yamauchi, A. 2006. Root development and nutrient uptake. Critical Reviews in Plant Sciences, 25, 279-301.

Wang, X. & Below, F. E. 1996. Cytokinins in enhanced growth and tillering of wheat induced by mixed nitrogen source. Crop Science, 36, 121-126.

Waterer, D. 1992. Influence of planting date and row covers on yields and crop values for bell peppers in Saskatchewan. Canadian Journal of Plant Science, 72**,** 527-533.

Waterer, D. 2003. Yields and economics of high tunnels for production of warm-season vegetable crops. Horticultural Technology, 13**,** 339-343.

Wells, O.S. 1991. High tunnels shelter early crops. American Vegetable Grower, 39**,** 44.

Zhang, H. & Forde, B.G. 2000. Regulation of Arabidopsis root development by nitrate availability. Botany, 51, 51-59.

Chapter 3: Gaseous exchange and photosynthetic efficiency of fertigated indeterminate tomatoes (*Solanum lycopersicum*) in response to trellising methods

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3.1 Abstract

Trellising is one of the important horticultural practices used during growth and development of tomatoes produced in tunnels and open fields. Vertical, early and late layering trellising methods are the most commonly used in tunnels, however, they have differences in light interception, which in turn affect productivity and quality. The objective of this study was to investigate the effect of different trellising methods on leaf gaseous exchange and photosynthetic efficiency of fertigated indeterminate tomatoes grown in a dome-shape tunnel. The experiment was arranged as a complete randomized block design, in the 8 m x 30 m dome-shape tunnel structure, with three treatments, namely, vertical, early layering and late layering trellising. Each treatment was replicated 3 times with each replicate consisting of 4 plants, resulting in 36 experimental units. The results showed significant differences ($p < 0.05$) amongst the different trellising methods in photosynthetic rate (A), intercellular CO_2 concentration (Ci), stomatal limitation ($1\text{-}Ci/Ca$), ratio of intercellular and atmospheric CO_2 concentration (Ci/Ca), transpiration rate (T), water use efficiency (WUE), maximum quantum efficiency of photosystem II photochemistry (Fv/Fm), maximum fluorescence (Fm), effective quantum efficiency of photosystem II photochemistry (ϕ PS II), electron transportation rate (ETR), photochemical quenching (qP) and proportion of open reaction centers (1-qP), indicating variability among tested trellising methods. The overall findings on leaf gas exchange and chlorophyll fluorescence revealed that early and late layering trellising methods improved photosynthetic efficiency than vertical trellising. Therefore, these results provide some evidence that early and late layering trellising are the best methods that can be used by resource-constrained farmers in dome-shape tunnel to improve physiological efficiency of indeterminate tomatoes.

Keywords: Chlorophyll fluorescence, gas exchange, trellising, photosynthetic efficiency, indeterminate tomato.

3.2 Introduction

The yield of tomato produced in open fields in South Africa is negatively affected by adverse environmental conditions (Maboko et al., 2011). With its tropical origin, the tomato plant requires a warm and dry climatic condition for optimum growth. On the other hand, a larger part of South Africa has a subtropical climate with hot temperatures and high relative humidity; as a result, this makes tomato plants to be more prone to pests and diseases. The use of protected cultivation of tomato in South Africa has gained popularity in the past decades due to the improvement of yield and quality (Du Plooy et al., 2012). Protected structures provide a certain degree of environmental control and reduce pest and disease occurrence (Wittwer and Castilla, 1995).

Tomato produced in tunnels requires numerous horticultural practices to achieve its potential yield. These horticultural practices include growing media, transplanting, optimum plant population, trellising, pruning, watering and fertigation. Trellising is one of the most important horticultural practices used to support vines and increase the yield of tomato produced in both tunnel and open field (Alam et al., 2016). Trellising is defined as the use of sturdy material to support tomato plant stem to keep fruit and foliage off the ground, increase light penetration and reduce pests and diseases (Alam et al., 2016). There are various types of trellising methods used for tomato production and these include vertical trellising, early layering trellising, late layering trellising, basket weave trellising, netting trellising and so on. In tunnel production, the most used trellising methods for tomato production are vertical trellising, early layering and late layering trellising method (Lecuona, 2013). These trellising methods are achieved by securing tomato plants with a plastic twine and hang on a horizontal wire running at a height of ± 2 m above the ground. However, these methods have differences in trellising positions. Vertical trellising for instance as the name implies is achieved by trellising plants in a vertical direction while early layering trellising is achieved by trellising plants in a diagonal direction. Late layering trellising, on the other hand, plants are allowed to grow in a vertical direction until they reach the maximum level of the tunnel and later trellised in a layering trellising method.

The most common trellising method used under commercial tunnel production systems is vertical trellising. This is efficient and sustainable under commercial operating tunnels with high roofs and systems to filter solar radiation. However, this trellising method has some limitations in small-scale farming systems using dome-shaped tunnel structures. This is mainly because tomatoes grow tall reaching the heights of 3 - 6 m before reaching its expected growth (Lecuona, 2013). Dome-shape plastic tunnels are usually 2 - 3 m tall and temperatures at this height are sometimes very high, especially during the hot summer days (Owen et al., 2016). As a result, the plants reach the highest point of the tunnel structure before the attainment of its yield potential. It has been observed that apical meristem at high temperatures are burnt by the heat of the plastic roof and plants end up dying earlier before the crop has produced its potential yield. To overcome this problem, layering trellising has been used for many years as an alternative method to solve the problems associated with height and it is known to improve the lifespan and yield of tomato in dome-shaped tunnels (Lecuona, 2013). However, there are cases where farmers use this layering trellising method, keeping the plant growing for a longer period but still do not achieve the crop potential yield. This is hypothesized to be linked to the timing of trellising because most farmers allow plants to grow vertically until they reach the maximum level of the tunnel and late applying layering trellising.

Late layering trellising of tomato plants changes the original orientation of the plant and that might also affect the orientation of the vascular system. Furthermore, trellising causes the mechanical disturbance on tomato plants such as bruising and bending which might have a negative influence on crop physiology. Kim et al. (2004) found that bending of the stem in roses reduces photosynthetic rate, stomatal conductance and transpiration, plants recovered to normal physiological processes after 21 days. The authors attributed this decrease to the compression of xylem, thus resulting in a decrease in water transportation. In another study, Schubert et al. (1995) found that trellising *Vitis vinifera*, the common grape vine, in a horizontal direction reduce photosynthesis and yield compared to upward trellising. Similar results were also reported by Reynolds and Heuvel (2009), that *Vitis vinifera* results in reduced photosynthesis and yield when trellised in a horizontal direction compared to vertical trellising. These authors attributed the decrease in photosynthesis of horizontal trellis to the reduced light interception by the leaves. However, little information has been reported on the tomato training system and timing effects on photosynthetic efficiency. Such studies are important to select the best trellising method particularly for limited resourced farmers, which mostly grow tomatoes in dome-shaped tunnels characterized by height limitations. However, what is apparent is that the type of trellising method may lead to different leaf area and percentage of leaves exposed to light. Consequently, the ability of tomato plants to photosynthesize efficiently depends on its trellising system and accompanying light microclimate. In addition, trellising may also impact other variables such as trellis water status, fruit bud differentiation and transpiration.

Therefore, the objective of this study was to investigate the effect of different trellising methods on leaf gaseous exchange and photosynthetic efficiency of fertigated indeterminate tomatoes grown in a dome shape tunnel.

3.3 Materials and methods

3.3.1 Plant material

Tomato (*Solanum lycopersicum*) seedlings of the hybrid variety STAR 9037 (Starke Ayres, Pietermaritzburg, South Africa) used in this study were sourced from the local commercial nursery (Sunshine Seedlings®, Pietermaritzburg, South Africa). This hybrid variety is one of the most cultivated in South Africa under protected structures.

3.3.2 Controlled environmental condition

The study was conducted in the 8 m x 30 m dome-shaped tunnel structure covered with polyethylene plastic, during summer months of 2018/19 season, starting from November 2018 to April 2019. The tunnel structure was located at Ukulinga Research Farm of the University of KwaZulu-Natal, in KwaZulu-Natal Province, South Africa (29°40'05.7"S 30°24'20.9"E). The temperature (T) and relative humidity (RH) were measured using digital LCD display MT669 data logger (Major Tech, Elandsfontein, Johanenesburg, South Africa). Recorded temperature and relative humidity during the plant growing period were respectively at an average of 38 °C and 41% (Fig. 1).

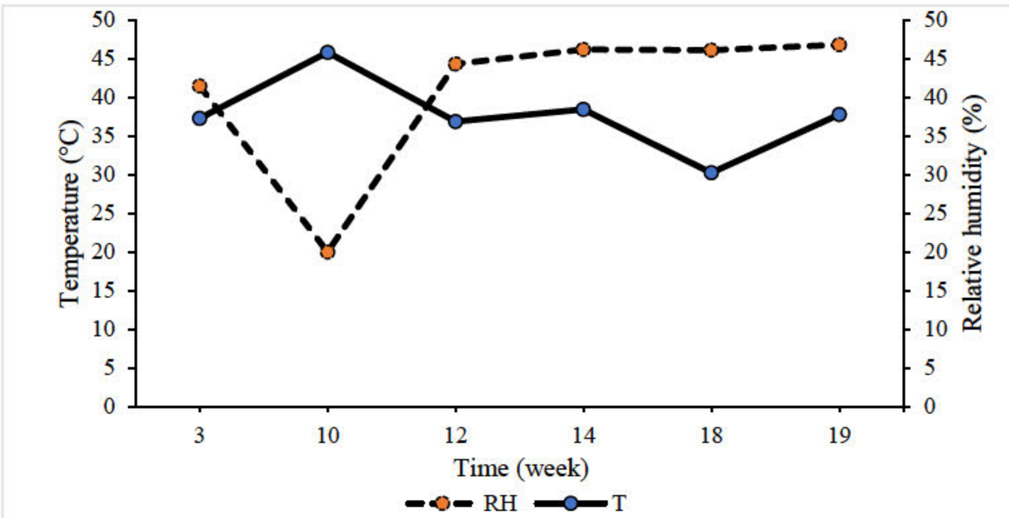

Fig. 6: The temperature and relative humidity recorded during the sampling dates

3.3.3 The experimental design and trial management

The experiment was arranged in a complete randomized block design with 3 treatments, namely, vertical trellising, early layering trellising and late layering trellising methods. Tomatoes on vertical trellising treatment were supported upward at an angle of 90° to the ground from the beginning of the experiment until they reached the highest point of the tunnel then after allowed to bend and grow in any direction (Fig. 2). On the other hand, plants on early layering trellising treatment were trellised at an angle of 45° to the ground from the second week after transplanting. Tomato plants assigned to late layering trellising treatment were trellised vertically until they reached the highest point in week twelve and later trellised at an angle of 45° to the ground. Each treatment was replicated 3 times with each replication consisting of 4 pots planted with two plant per pot. resulting in 36 experimental units (3 x 3 x 4). Pots were laid in a spacing of 50 cm in rows and 1.5 m between rows. Seedlings were six weeks old at the time of transplanting. These seedlings were transplanted into 8 L bags filled with fine pine sawdust as a growing medium. Water-soluble inorganic fertilizer mix (commercial fertilizer) in the form of Solucal® (calcium(190g/kg) nitrate (155g/kg)), Multi-K (potassium(380g/kg) nitrate (130g/kg)) and Hygroponic® (N (61.7 g/kg), P (34 g/kg), K (262 g/kg), B (651.9 mg/kg), Fe (2218 mg/kg), Mg (17.5 g/kg), Mo (63 mg/kg), Zn (645.5 mg/kg), Cu (86.5 mg/kg), Mn (508.9 mg/kg) and S (76.7 g/kg)) was dissolved in one tank filled with 5000 L of water. Fertilizers were mixed according to the recommendation by the manufacturer (Hygrotech SA, Pietermaritzburg, South Africa). The tank of 5000 L of water was mixed with 2.7 kg Solucal, 500 g multi-K® and 3 kg Hygroponic® from transplant to the third flower. After the third flower truss to the end, fertilizers were increased by mixing 5000 L of water with 3.5 kg Solucal, 1 kg Multi-K and 5 kg Hygroponic®.

Plants were fertigated by pumping fertilizer mix into an open-loop fertigation system. Each plant was fertigated for 5 minutes with a soluble fertilizer mix using a dripper emitting 2 L of dissolved fertilizer per hour. The plants were fertigated on a 2-hour interval from 7 am to 1 pm after which they were fertigated hourly until 4 pm. The plants were pruned on a weekly basis by removing sucker stems. Trellising was extended once a week using twines and hangers (Fig. 2).

Fig. 7: Tomato grown in a vertical (left) and layering (right) trellising method.

3.3.4 Data collection: measurement of photosynthetic parameters and chlorophyll fluorescence

Leaf gas exchange and chlorophyll fluorescence were measured at the same time using a Portable Photosynthesis System LI-6400 XT (Licor Bioscience, Inc. Lincoln, Nebraska, USA) fitted with infrared gas analyzer connected to a leaf chamber fluorimeter (LCF) (6400-40B, 2 cm^2 leaf area, Licor Bioscience, Inc. Lincoln, Nebraska, USA). The artificial saturated photosynthetic active radiation (PAR) was fixed at 1000 $\mu mol\ m^{-2}\ s^{-1}$ and reference CO_2 maintained at 400 $\mu mol\ mol^{-1}$. The first measurements were taken in the second week after transplanting and continues in a two-weeks interval on sunny days between 9h00 and 11h00. Sampling was made on one leaf of each plant representing a replicate. Photosynthetic gas exchange parameters including, photosynthetic rate (*A*), stomatal conductance (*gs*), transpiration rate (*T*), intercellular CO_2 concentration (*Ci*) and ratio of intercellular and atmospheric CO_2 (*Ci/Ca*) concentration were measured. The stomatal limitation was calculated using Eq. 1 (Dong et al., 2016).

Stomatal limitation = 1-*Ci/Ca* (1)

Where *Ci* represent intercellular CO_2 concentration and *Ca* is the atmospheric CO_2.

Water use efficiency (*WUE*) was calculated using Eq. 2, previously described by Mashilo et al. (2017) as the ratio of *A* and *T*.

$$WUE = \frac{A}{T} \qquad (2)$$

Chlorophyll fluorescence parameters were recorded by providing artificial saturated PAR 1000 µmol m^{-2} s^{-1}. Minimum (*Fo*) and maximum (*Fm*) fluorescence were recorded. Photochemical variables such as maximum quantum efficiency of photosystem II photochemistry (*Fv'/Fm'*), effective quantum efficiency of photosystem II photochemistry (*ΦPSII*), electron transport rate (*ETR* photochemical quenching (*qP*) and non-photochemical quenching (*qN*) were recorded. The proportion of open reaction centers were calculated using Eq. 3 (Shezi et al., 2019).

Proportion of open reaction centers = 1-*qP* (3)

3.3.5 Statistical analysis

All data collected from variables measured were subjected to analysis of variance (ANOVA) using GenStat Version 18th Edition (VSN International, Hemel Hempstead, UK). Mean values recorded were separated using Fischer's least significant difference (LSD) test at 5% level of significance.

3.4 Results

3.4.1 Leaf gas exchange in response to different trellising methods

Photosynthetic rate (*A*) was significantly higher ($p < 0.05$) in the late trellising method than in early and vertical trellising methods (Table 1). Similar trends with slight differences were found in *T* which was observed to be higher in late and early trellising methods than in vertical trellising method. *ΦPSII* was also high ($p < 0.05$) in early and late trellising methods as compared to the vertical trellising method (Table 2). This indicated the higher rate of photosynthesis in early and late trellising methods than in vertical trellising methods. On the other hand, there were no differences ($p > 0.05$) found in gs whereas *Ci/Ca* was significantly lower under the late trellising method as compared to other treatments. Late layering and vertical trellising methods were associated with higher ($p < 0.05$) *WUE* than early layering trellising method (Table 1).

All gaseous exchange parameters varied significantly ($p < 0.01$) with time (Figs. 3A – 3G). Photosynthetic rate (*A*) was higher in the early stages of development (3 – 10 weeks after transplanting) and declined significantly in all trellising methods from week 12 after transplanting onwards. The general trend was that the late trellising method was found to have a higher *A* in most cases as compared to early and vertical trellising methods. In contrast, *T* (Fig. 3E) decreased with time with no clear trends between the treatments while on the other hand, *WUE* followed a similar trend as that of *A*. *WUE* was higher in most cases in late, vertical and early trellising methods respectively. During the sampling period, the highest *WUE* was observed on week 10 (Fig. 3F) amongst all the treatments. The early layering trellising method showed significantly increased in *Ci*, despite the decrease in gs compare to vertical and late layering trellising. Contrary to changes that were observed in *Ci* in respect of evaluation time (Fig. 3C). *Ci/Ca* ratio and *Ci* followed a similar trend of increasing and decreasing over the sampling period (Fig. 3D). The obtained results revealed that 1-*Ci/Ca* was inversely proportional to *Ci* and *Ci/Ca*. During the time of evaluation increase in *Ci* and *Ci/Ca* ratio was the decrease in 1-*Ci/Ca* (Fig. 3G).

Table 3: Average leaf gas exchange variables of hydroponically produced tomatoes in response to different trellising methods

Trellising method	Leaf gas exchange parameters						
	A	***gs***	***Ci***	***Ci/Ca***	**1-*Ci/Ca***	***T***	***WUE***
Early layering	32.14ab	-1.459a	362.0b	0.940b	0.059a	16.55b	2.091a
Late layering	36.27b	-1.552a	342.6a	0.893a	0.106b	14.21ab	2.799b
Vertical	31.25a	-1.512a	349.9ab	0.907ab	0.092ab	13.02a	2.518b
$LSD_{(0.05)}$	2.292	0.259	15.29	0.040	0.040	2.374	0.335

A**: photosynthetic rate (µmol CO_2 m^{-2} s^{-1}),** ***gs*****: stomatal conductance (mmol CO_2 m^{-2} s^{-1}),** ***Ci*****: intercellular CO_2 concentration (µmol mol^{-1}),** ***Ci/Ca*****: ratio of intercellular and atmospheric CO_2 concentration, 1-*Ci/Ca*: stomatal limitation,** ***T*****: transpiration rate (mmol H_2O m^{-2} s^{-1}),** ***WUE*****: water use efficiency (µmol (CO_2) m^{-2} (H_2O)).**

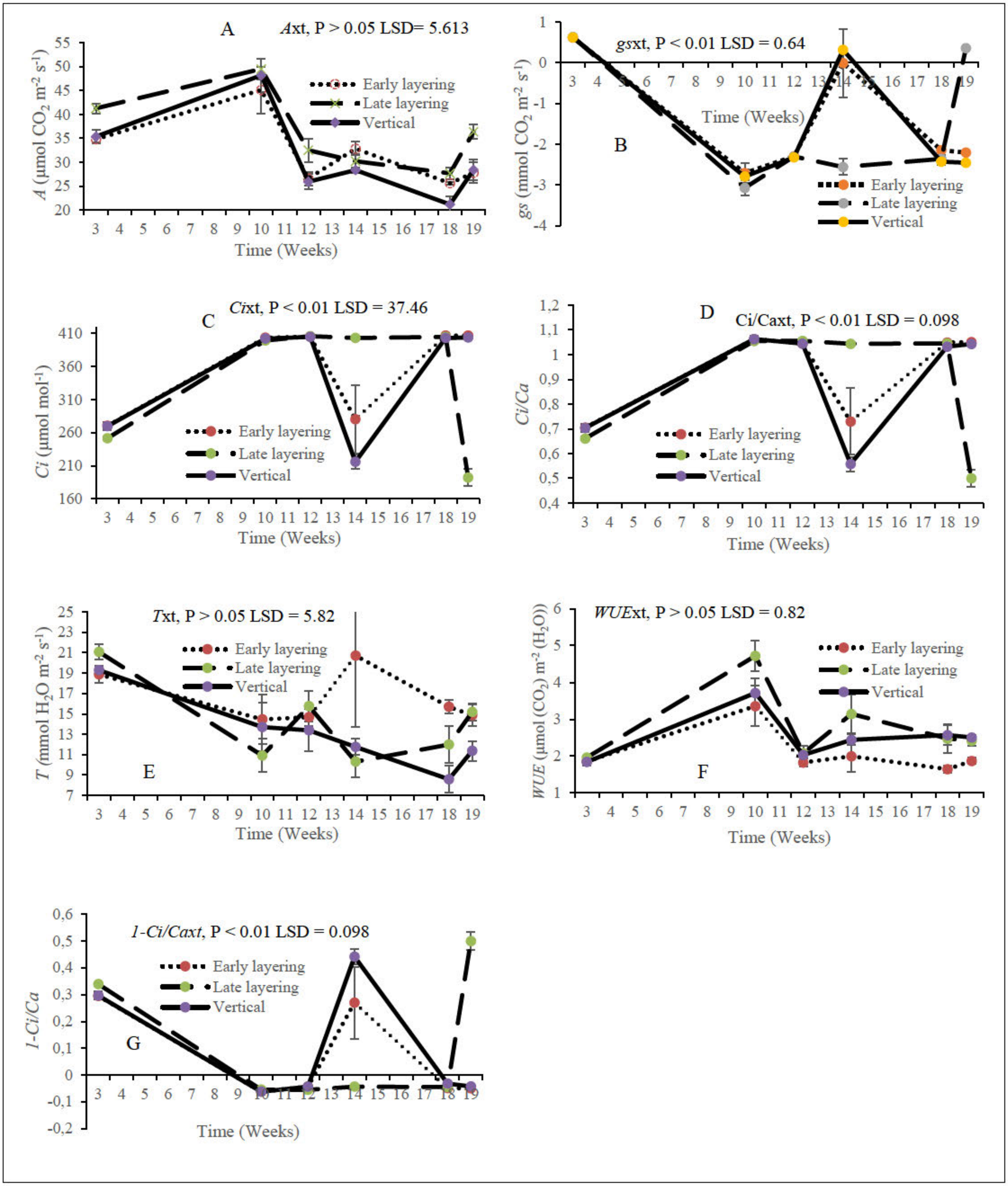

Fig. 3: Weekly effect of different trellising methods on leaf gas exchange parameters of indeterminate tomato produced hydroponically in dome shape tunnels. Photosynthetic rate (A), stomatal conductance (B), intercellular CO_2 (C), ratio of intercellular and atmospheric CO_2 concentration (D), transpiration rate(E), water use efficiency (F) and stomatal limitation (G).

3.4.2 Chlorophyll fluorescence in response to different trellising methods

Significant differences ($p < 0.05$) were observed in all measured chlorophyll fluorescence parameters with respect to trellising methods and time (Fig. 4A – 4F). Trellising methods showed significant differences with regards to *Fm*'. Early layering trellising showed an increase in *Fm*'(1361 µmol m^{-2} s^{-1}) compare to vertical trellising (1271 µmol m^{-2} s^{-1}) and late layering (1267 µmolm^{-2} s^{-1}) method (Table 2). Fv'/Fm' varied significant ($p < 0.05$) with trellising methods, early layering trellising had a higher value of 0.684 compared to late layering and vertical trellising methods which are respectively showed the lowest value of 0.654 and 0.649 (Table 2). Trellising methods variability in respect of *ΦPSII* was observed. Late layering trellising and early layering showed respectively a higher value of *ΦPSII* compare to vertical trellising methods (Table 2). *ΦPSII* also varied significantly ($p < 0.01$) with time where on average it was higher in the late trellising method (Fig. 4C). *ETR* followed the same trend as in *ΦPSII* (Table 2 & Fig. 4E). *qP* exhibited a significant increase with late layering trellising had shown a value of 0.55 (Table 2). The lowest value of *qP* was observed in early layering and vertical trellising had shown 0.484 and 0.454, respectively. *qP* also varied significant ($p < 0.01$) with time of sampling (Fig. 4D). 1-*qP* of *PSII* varied significantly ($p < 0.05$) with trellising methods and time of sampling (Fig. 4F). Vertical trellising and early layering trellising with 1-*qP* recorded a higher value of 0.546 and 0.516 respectively. Lower *1-qP* value of 0.450 was recorded on late layering trellising.

Table 2. Average chlorophyll fluorescence variables of hydroponically produced tomatoes in response to different trellising methods

Trellising method	Chlorophyll fluorescence parameters						
	Fo	***Fv'Fm'***	***ΦPSII***	***qP***	***ETR***	**1-*qP***	***Fm'***
Early layering	421.5a	0.684b	0.333b	0.484a	183089b	0.516b	1361b
Late layering	426.8a	0.654a	0.359b	0.55b	196707b	0.449a	1267a
Vertical	428.5a	0.649a	0.294a	0.454a	160319a	0.546b	1271a
$LSD_{(0.05)}$	34.16	0.028	0.035	0.057	19113.1	0.057	89.3

Fo: **minimum fluorescence, *Fm*: maximum fluorescence, *Fv'Fm'*: maximum quantum efficiency of photosystem II photochemistry, *ΦPSII*: the effective quantum efficiency of photosystem II photochemistry, *qP*: photochemical quenching, *ETR*: electron transportation rate and 1-*qP*: the proportion of open reaction centers.**

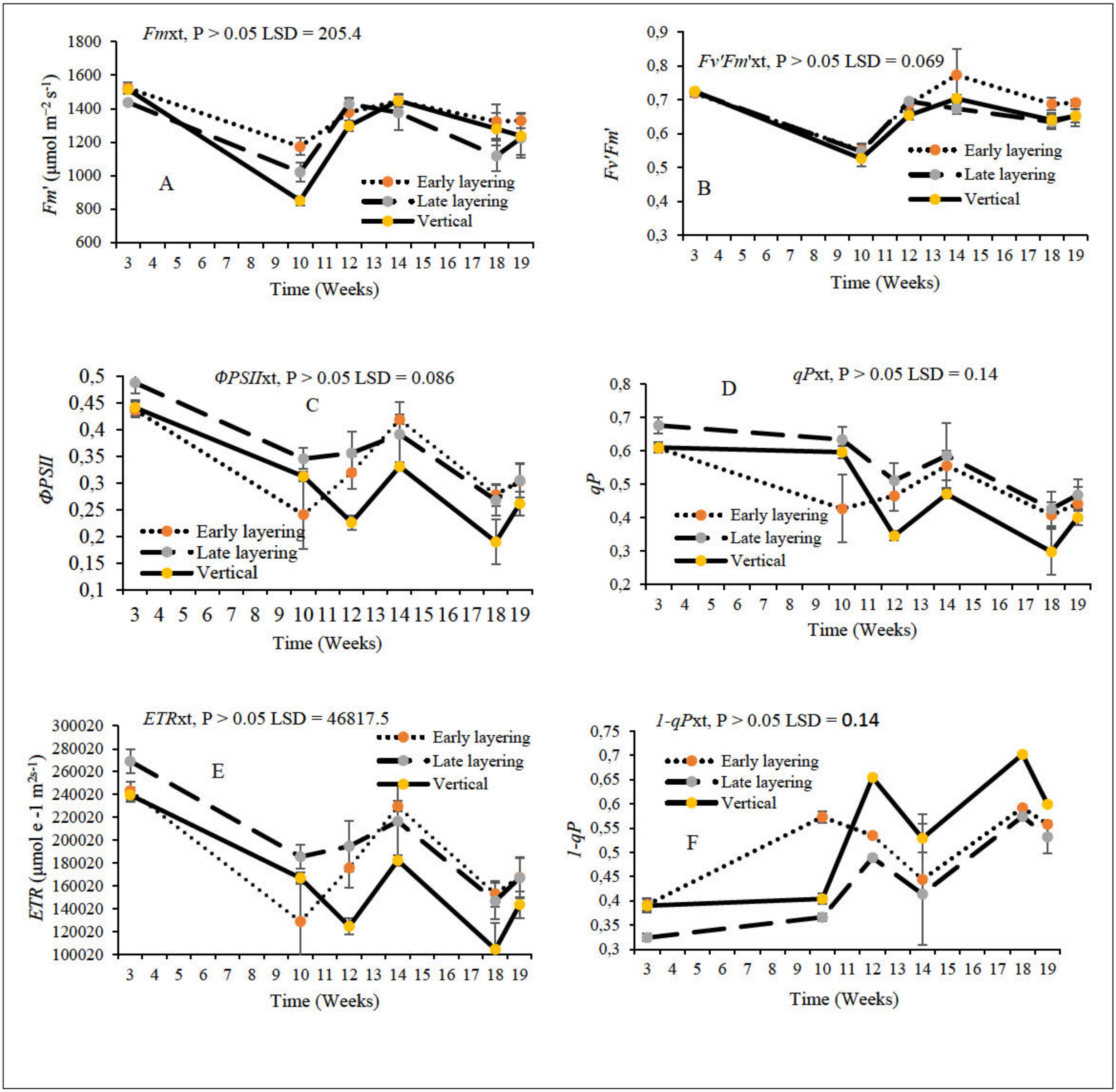

Fig. 4: Weekly measurements of chlorophyll fluorescence variables in response to different trellising methods of indeterminate tomatoes produced hydroponically in dome shape tunnels. Maximum fluorescence (A), maximum quantum efficiency of photosystem II photochemistry (B), the effective quantum efficiency of photosystem II photochemistry (C), photochemical quenching (D), electron transport rate (E) proportion of open reaction centers (F).

3.5 Discussion

Photosynthesis is the essential biological process, which enables plants to access energy from sunlight and utilize it for growth, development and the production of yield. Therefore, understanding the photosynthetic efficiency of the tomato plant is crucial for designing suitable cultural practices important to increase yield. The present study investigated the effect of different trellising methods on indeterminate tomato grown in dome shape tunnels based on leaf gas exchange and chlorophyll fluorescence to identify the most promising trellising method associated high carbon fixation and/or photosynthesis rate. The study exhibited that there were no significant differences among the treatments in stomatal conductance (*gs*). Stomatal conductance measures the rate of carbon dioxide entering the leaf through stomata (Shezi et al., 2019).

The present study also found that the early and late layering trellising methods increased *A* compare to the vertical trellising method. The decrease in *A* of vertical trellising was not related to stomatal limitation since gs was not variable among trellising methods in turn which may mean that other parameters may have played a role in *A* differences. During the time of evaluation, *A* after transplanting was increasing in all treatments until week 10, after that, it declined in all the treatments. This variation may have resulted from the changes in the seasons, from summer to the autumn, which interfered with the temperature in the semi-controlled environment in the tunnel. The results also showed that *A* of late layering and vertical trellising was higher than early layering from week 3 up to week 10. These findings revealed that during early stages of growth vertical and late layering trellising were exposed to high light intensity since they were growing vertically whereas early layering trellising was receiving less light since it was growing at an angle of 45° to the ground and some leaves were shaded against another hence receiving less light. In week 14, early layering had exhibited high *A* until week 16 where early and late layering was slightly increasing with similar trends after late layering was trellised in the same direction as early layering.

Tomato produced in the vertical trellising method, at the later stage of growth becomes close to the roof plastic and exposed to high intensity of light and temperature. Therefore, heat stress inhibits photosynthesis through the reduction of ribulose-1,5-bisphosphate (RuBP) supply impacted by low ATP synthesis (Tezara et al., 1999) or inhibition in chloroplast activity (Shangguan et al., 1999). Similar results were found by Hassan (2006) in drought and heat stress of *Triticum aestivum* where *Pn* was significantly reduced. Internal CO_2 and the ratio of *Ci/Ca* directly depended on the opening and closing of stomata and when stomata open *Ci* increase and *Ca* as the numerator also increase, resulting to increase *Ci/Ca* (Shezi et al., 2019). The current study found an increased *Ci* and *Ci/Ca* with early layering and vertical trellising. During the plant growing period *Ci* and *Ci/Ca* of all treatments were increasing with similar rates until week 14 where vertical and late layering had a decline. These findings further confirmed that the increase and decrease of *A* on trellising methods was not in conjunction with stomatal limitation. Similar results where *Ci* increased despite the decrease of *A* were observed in drought-stressed bottle gourd landraces (Mashilo et al., 2017) and water-stressed cowpea as compared to non-stressed treatments (Singh and Reddy, 2011). Transpiration is a water vapour lost by plant through stomatal pores. The current study showed an increase *T* and decrease *WUE* in early layering trellising while vertical and late layering had lower *T* and higher *WUE*. The decline of *WUE* with layering trellising was caused by the high amount of water loss as vapour which can be used otherwise by the plant.

Chlorophyll fluorescence measurement is an indicator of photosynthesis activity and used to estimate the protection mechanism involved in the removal of excessive heat (Maxwell and Johnson, 2000; Baker and Rosenqvist, 2004). In the present study, the result showed no significant differences in *Fo* suggesting that the tested plants had no variation among different trellising methods. Early layering trellising showed an increase in *Fm*'. The *Fm'* is maximal fluorescence level occur when high-intensity flash has been applied. The antenna sites during this process are assumed to be closed, reflecting a state of electrical transfer when passed *PSII* (Baker and Rosenqvist, 2004).

The current study also found an increase of *Fv'Fm'* with early layering trellising method and lower in late layering trellising and vertical trellising method. Fv'Fm measures the maximum efficiency of light absorbed by *PSII* antennae is converted to chemical energy. The increase in *Fv'Fm'* in early layering trellising suggested a protective mechanism of the photosystem from photo inhibitory damage. The observed results also showed *Fv'Fm'* of treatments increasing and decreasing with a similar trend over time until week 12 where early layering was increasing more than vertical and late layering trellising. The decrease of *Fv'Fm'* in late layering and vertical trellising may also mean the susceptibility of tomato plants to photosynthesis inhibition. *ΦPSII* estimates the effectiveness of excitation energy absorbed by chlorophyll a used for photochemistry. The current study found higher *ΦPSII* in early and late layering trellising, which suggests efficient light utilization for photosynthesis in these treatments. On the other hand, the decrease in *ΦPSII* of vertical trellising suggested a decrease in chlorophyll synthesis resulting to reduced photosynthesis.

The presented results also exhibited higher *ΦPSII* in late layering and vertical trellising than early layering during the earliest period of growth until week 12 where early layering had shown an increase than other treatments. These findings further confirm that plants trellised in vertical position decrease photosynthesis once they reach the maximum height of the tunnel. Photochemical quenching (*qP*) and non-photochemical (*qN*) quenching are the two processes occurred in the removal of excess light (Shezi et al., 2019). *qP* determine the proportion of *PSII* open reaction centers and measure the energy used for photosynthesis (Maxwell and Johnson, 2000). The present study found higher *qP* in late layering suggesting that more *PSII* centers were kept in an open state and more excitation energy was used for electron transportation. Decrease of *qP* in early layering and vertical trellising methods suggest susceptibility to photo inhibition. *qN* is a protective mechanism that prevents damage impacted by excessive light energy reaching the photosynthetic apparatus (Maxwell and Johnson, 2000). The current study found no significant differences among trellising methods and time. This means there were no differences among the trellising method in the removal of excess excitation energy via thermal dissipation. The present study also found an increase in electron transportation in late layering and early layering and accompany with a respectively lower 1-*qP* in late and early layering.

Similar results were reported by Shezi et al. (2019) where the outside canopy with high *ETR* had low *1-qP*. This result may mean lower proportions of 1-*qP* were due to the fast rate of electron transportation in that way the system in the reaction centers was always closed. The fast rate of electron transportation resulted in a fast rate of overall photosynthesis. The presented results also showed a high electron transportation rate and lower 1-*qp* in late layering and vertical trellising than early layering from transplant until week 12 where both early and late layering showed an increase with a slight similar trend. Presented findings confirm that vertical trellising at a late stage of growth gets the plants exposed to high heat, thus, resulting to photosynthesis inhibition.

3.6 Conclusion

The present study evaluated the influence of different trellising methods on leaf gas exchange and chlorophyll fluorescence. Variability among the tested trellising methods was observed. Early and late layering had higher *A*, *T*, *ΦPSII* and *ETR* compared to vertical trellising. Height limitation and burning of epical meristem in dome shape tunnel is one of the major setback associated with vertical trellising. The observed high *ETR* and lower 1-*qP* in vertical trellising from transplanting until week 12 and a decline after while early and late layering were increasing with a slightly similar trend confirmed the hypothesis that vertical trellising reduces the photosynthetic rate at a late stage of growth because of exposure to high temperature. Therefore, the presented results have given some indications that early and late layering trellising methods can be the best methods that can be used by resource-constrained farmers in dome shape tunnel to increase physiological efficiency, which may be linked to yield.

3.7 References

Alam, M., Islam, N., Ahmad, S., Hossen, M. & Islam, M. 2016. Effect of different staking methods and stem pruning on yield and quality of summer tomato. Bangladesh Journal of Agricultural Research, 41, 419-432.

Baker, N.R. & Rosenqvist, E. 2004. Applications of chlorophyll fluorescence can improve crop production strategies: an examination of future possibilities. Journal of Botany, 55**,** 1607-1621.

Dong, C., Shao, L., Wang, M., Liu, G., Liu, H., Xie, B., Li, B., Fu, Y. & Liu, H. 2016. Wheat carbon dioxide responses in space simulations conducted at the Chinese Lunar Palace-1. Agronomy Journal, 108**,** 32-38.

Du Plooy, C., Maboko, M., Van Den Heever, E. & Chiloane, S. 2012. Research and technology transfer by the Agricultural Research Council to sustain the South African hydroponic industry. Acta Horticulturae, 947**,** 147-152.

Hassan, I. 2006. Effects of water stress and high temperature on gas exchange and chlorophyll fluorescence in *Triticum aestivum L.* Photosynthetica, 44**,** 312-315.

Kim, S.H., Shackel, K.A. & Lieth, J.H. 2004. Bending alters water balance and reduces photosynthesis of rose shoots. Journal of the American Society for Horticultural Science, 129**,** 896-901.

Lecuona, A. 2013. Trellising tomato plants in a greenhouse. https://www.commercial-hydroponic-farming.com/trellising-tomato-plants/. Last accessed: 20 May 2019.

Maboko, M., Du Plooy, C. & Chiloane, S. 2011. Effect of plant population, fruit and stem pruning on yield and quality of hydroponically grown tomato. African Journal of Agricultural Research, 6**,** 5144-5148.

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 Physiology and Biochemistry, 120, 75-87.

Maxwell, K. & Johnson, G.N. 2000. Chlorophyll fluorescence a practical guide. Journal of Botany, 51, 659-668.

Owen, W.G., Hilligoss, A. & Lopez, R.G. 2016. Late-season High Tunnel Planting of Specialty Cut Flowers in the Midwestern United States Influences Yield and Stem Quality. Horticultural Technology, 26, 338-343.

Reynolds, A.G. & Heuvel, J.E.V. 2009. Influence of grapevine training systems on vine growth and fruit composition: a review. American Journal of Enology and Viticulture, 60, 251-268.

Schubert, A., Restagno, M., Novello, V. & Peterlunger, E. 1995. Effects of shoot orientation on growth, net photosynthesis, and hydraulic conductivity of *Vitis vinifera L*. cv. Cortese. American Journal of Enology and Viticulture, 46, 324-328.

Shangguan, Z., Shao, M. & Dyckmans, J. 1999. Interaction of osmotic adjustment and photosynthesis in winter wheat under soil drought. Journal of Plant Physiology, 154, 753-758.

Shezi, S., Magwaza, L.S., Mashilo, J., Tesfay, S.Z. & Mditshwa, A. 2019. Photosynthetic efficiency and relationship to mesocarp dry matter content of 'Carmen'avocado (*Persea americana Mill.*) fruit in a cool subtropical climate. Scientia Horticulturae, 253, 209-216.

Singh, S.K. & Reddy, K.R. 2011. Regulation of photosynthesis, fluorescence, stomatal conductance and water-use efficiency of cowpea (*Vigna unguiculata [L.]* Walp.) under drought. Journal of Photochemistry and Photobiology B: Biology, 105, 40-50.

Tezara, W., Mitchell, V., Driscoll, S. & Lawlor, D. 1999. Water stress inhibits plant photosynthesis by decreasing coupling factor and ATP. Nature, 401, 914.

Wittwer, S.H. & Castilla, N. 1995. Protected cultivation of horticultural crops worldwide. Horticultural Technology, 5, 6-23.

Chapter 4: Investigating the influence of trellising methods on growth, yield and quality of indeterminate tomato produced in dome shape tunnels

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4.1 Abstract

Tomato production in protected cultivation faces numerous agronomic constraints that should be overcome to fight malnutrition for the growing population. The adoption of improved horticultural practices aimed at maximizing yield and performance of tomatoes grown in protected cultivation has been identified as one of the strategies that could be effective to solve this challenge. This study evaluated the effect of layering trellising technique on growth and yield performance of indeterminate tomato cultivars. The experiment was laid out in a complete randomised design replicated three times, with each replication represented by 4 plants. The experimental treatment included; early layering, late layering and vertical trellising (control). Results showed significant difference ($p < 0.05$) with growth and yield parameters in response to different trellising methods. Photosynthetic rate (*A*) showed slightly increase with late layering 36.27 (µmol CO_2 m^{-2} s^{-1}) and early layering 32.14 (µmol CO_2 m^{-2} s^{-1}) trellising than vertical trellising 31.25 (µmol CO_2 m^{-2} s^{-1}). Similarly, plant height on evarage showed slightly increase with early (126.28 cm $plant^{-1}$) and late layering trellising (124.33 cm $plant^{-1}$) compare to vertical trellising (121.37 cm $plant^{-1}$). On the other hand, vertical trellising exhibited an evarage of higher stem diameter (10.91 mm $plant^{-1}$) than early layering (10.40 mm $plant^{-1}$) and late layering trellising (10.33 mm $plant^{-1}$). Early and late layering had high fruit number (6.47 and 5.67 fruit $plant^{-1}$) and fruit mass in each harvest (132.2 and 131.2 g $plant^{-1}$) compared to vertical trellising. The results exhibited no significant differences among trellising methods with respect to quality parameters. Colour index showed significant interaction between trellising methods and harvest time. The general trend was that early layering found to have higher colour index compared to vertical and late layering. Therefore, the overall results reveal that early and late layering was most promising to be used as an alternative method

to substitute vertical trellising if farmers seek to increase their yield and maximize profit in dome shape tunnels. However, in order to establish the influence of temperature on plant growth and yield, the effect of layering trellising methods during the winter months should be investigated.

Keywords: Trellising methods, indeterminate tomato, dome shape tunnels, Temperature, yield, quality.

4.2 Introduction

Worldwide production of tomatoes (*Solanum lycopersicum*) has tremendously increased during the last two decades, from 109 M tons in 1999 to 182 M tons in 2018 (FAO, 2019). However, the demand of large yield still exist globally and many countries are still failing to produce enough yield of tomatoes to satisfy the nutritional needs of growing population, especially in sub- Saharan Africa (SSA). Yields of open field tomatoes generally range between 40 and 100 t ha^{-1} depending on cultural practices and agro- climatic conditions (Heuvelink, 2005). However, the average yield in some countries is estimated to be less 19.4 t ha^{-1} (FAO, 2013). Open field production of tomatoes faces various biotic problems such as, weeds, insect pests and diseases, as well as abiotic problems including floods, drought and low soil fertility. As a result, its productivity is influenced to a great extent by climatic conditions leading to marked seasonal variations in supply. The high increase economic value, high labour requirements, and small cultivated area for tomato production have favoured the use of protected cultivation technique (PCT) to reduce the effect of biotic and abiotic limiting factors thereby increasing the production level. Protected cultivation technique includes the use of mulching, row covering and high shelters/tunnels with an objective to simulate the natural environment to accomplish optimal plant growth conditions. This provides the grower with multiple benefits such as season extension, protection against harsh weather conditions and reduced pressure against pest and diseases (Mitchell et al., 2019).

Although protected cultivation has been identified as a promising technology that enables the continuous availability and supply of tomatoes, it is worth nothing that the effects of high tunnels vary greatly with the climatic conditions, agronomic constraints and pest pressure. The physical support provided by high tunnels encourages the use of trellising systems to cultivate indeterminate cultivars since it facilitates crop handling, extends the production period and increases yield. Trellising has been long identified as one of the most essential horticultural practices used to improve yield and quality of tomato produced in high tunnels. It involves the use of strong material to support tomato stem upright since it is herbaceous, and to keep fruits and foliage off the ground. It also increases light interception, and reduce the chances of pest and diseases (Alam et al., 2016). The yields of indeterminate tomato cultivars cultivated in plastic tunnels are reported to increase up to 700 t ha^{-1} depending on cultural practices and climatic conditions with a production period of 11 to 12 months, in contrast to yields of up to 100 t ha^{-1} and a production period of 3 to 4 months for determinate tomatoes (Heuvelink, 2005). As a result, the use of high tunnels and indeterminate tomato cultivars is considered more viable because it is able to offset the agronomic constraints endangered by open field production such as, water stress, poor pollination, soil-borne diseases, and low soil fertility.

Currently, several types of trellising methods are used for tomato production, however, the most common used for tunnel production includes vertical trellising, early and late layering trellising method (Lecuona, 2013). These trellising methods are achieved by securing tomato plants with a plastic twine and hang the stem along a horizontal wire running at a height of ± 2 m above the ground. Vertical trellising is achieved by trellising plant in an upward direction while early layering is achieved by trellising plant in a diagonal direction during the early growth stages of the plant. Late layering is the form of trellising which involve the combination of vertical and layering in which plants are allowed to grow in a vertical direction until they reach the maximum level of the tunnel and later trellised to face a diagonal direction. Basically, these types of trellising are distinguished by the direction in which the plants take during training and their selection is mostly informed by type of cultivar planted and the height of the tunnel. Vertical trellising method is commonly used in commercial tunnel production system where high roof tunnels are used in order to control inside temperature and relative humidity. However, the use of this method has a big challenge in small-scale farming systems using small structures particularly, dome-shaped tunnel because it is limited to the height of the tunnel. Since indeterminate tomato plant grows up to the height of 3 - 6 m, it is not possible to use vertical trellising method in dome shape tunnel because their height is only 2 – 3m tall. As problems are bound to occur especially during summer days when temperatures are very high, which might burn the apical meristem thereby affecting the yield potential of the crop (Owen et al., 2016; Lecuona, 2013). To alleviate this problem, layering trellising has since been used as an alternative method to overcome the problem associated with height limitation and known to improve tomato plant life span and yield (Lecuona, 2013). However, there are cases where farmers used this method and reported delayed maturity which compromised the targeted yields. The reduced in yield is assumed to be linked to the timing of trellising because most farmers apply layering trellising after the plant has already reach the maximum height of the tunnel. On the other hand, late layering trellising alter original orientation of tomato plant which might also influence the partitioning of vascular system.

Trellising tomato plant is also known to cause mechanical damage such as bruising and bending, this might have a negative influence on the plant physiology. Kim et al. (2004) found that bending of the stem in roses reduces photosynthetic rate, and plants undergo to a stress and recovered to normal physiological processes after 3 weeks. The reduction in the rate of photosynthesis is assumed to be linked to the damage in vascular tissues, which negatively affect the translocation of water and nutrients to other plant tissues. Reynolds and Heuvel (2009), reported that trellising *Vitis vinifera* in a horizontal direction reduced photosynthesis and yield compared to vertical trellising. These authors attributed the decrease in photosynthesis of horizontal trellis to the reduced light received by the leaves. However, there is too little information available in the literature with regard to the effects of layering as a trellising method and its timing on growth and yield performance of indeterminate tomato cultivars. The existing gab suggests the need for more research which focuses on the selection of the best trellising method particularly for farmers growing tomatoes under dome-shaped tunnels characterized by height limitations. Therefore, the objective of this study was to evaluate the influence of different trellising methods on growth and yield performance of indeterminate tomatoes produced in a dome shape tunnel.

4.3 Materials and methods

4.3.1 Plant material and controlled environmental condition

Six weeks old tomato seedlings of hybrid star 9037 were purchased from local commercial nursery (Sunshine Seedlings® Pietermaritzburg). The experiment was conducted at the University of KwaZulu-Natal Research Farm, in KwaZulu-Natal Province, South Africa (29°40'05.7"S 30°24'20.9"E) in a dome shape tunnel covered with a polyethylene plastic. The experiment commenced from November 2018 to April 2019. The average mean and maximum temperature and relative humidity ranged between (30 and 38 °C) and (35 and 41%), respectively for the entire growth season.

4.3.2 Experimental design and crop establishment

The study was designed in a complete randomized design with three replications each represented by four plants. The experimental treatments included three trellising methods namely; early layering, late layering and vertical (control) trellising methods. For early layering, plants were trellised at an angle of 45° from the beginning of plant growth till the end of its life cycle. The late layering trellising were achieved by allowing the plants to grow as vertical from the beginning and later after it has reached the maximum level of the roof, then trellised at angle of 45°. Plants assigned to vertical trellising methods were supported to grow upwards until they reach the maximum level of the tunnel roof where they were allowed to grow to any direction. These treatments were replicated three times with each replication consisting of 4 pots planted with two plant per pot, giving total number of thirty-six experimental units. Seedlings were transplanted to 8 L bags filled with pine shavings as a growing medium. Plants were fertigated using 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 essential micronutrients and macronutrients). These fertilizers were all dissolved in 5000 L tank of water. Using mixing instructions according to the recommendation by the manufacturer (Hygrotech SA, Pietermaritzburg, South Africa). The tank of 5000 L of water was filled with 2.7 kg Solucal (calcium(190g/kg) nitrate (155g/kg)), 500g Multi-K (potassium(380g/kg) nitrate (130g/kg)) and 3kg Hygroponic® (N (61.7 g/kg), P (34 g/kg), K (262 g/kg), B (651.9 mg/kg), Fe (2218 mg/kg), Mg (17.5 g/kg), Mo (63 mg/kg), Zn (645.5 mg/kg), Cu (86.5 mg/kg), Mn (508.9 mg/kg) and S (76.7 g/kg)) from transplant to the third flower. After the third flower truss to the end, fertilizers were increased by mixing 5000 L of water with 3.5 kg Solucal, 1 kg Multi-K and 5 kg Hygroponic®. Water pH was maintained between 5.6 – 5.8 and EC maintained between 1.8 – 2.5. Plants were irrigated using drippers emitting 2L/hour and irrigation were performed at six intervals (5 min/interval) daily using a timer. Pruning of older leaves and suckers were performed every week. Trellising on the other hand was done by hanging tomato plant on a horizontal wire running at the top of the plants using twines and hangers. Trellising was performed every week.

4.3.3 Data collection

4.3.4 Growth, photosynthesis and yield parameters

Plant height was measured using a flexible tape measure to accommodate the bending of the stem in a layering trellising. Measurement was taken from the base of the stem up to the tip of the stem. Stem diameter was measured using a caliper placed at the base of the stem. Measurement were taken in a two weeks interval. Photosynthetic rate (*A,* µmol CO_2 m^{-2} s^{-1}) was measured using a Portable Photosynthesis System LI-6400 XT (Licor Bioscience, Inc. Lincoln, Nebraska, USA) connected with an infrared gas analyzer fitted to a leaf chamber fluorimeter (LCF) (6400-40B, 2 cm^2 leaf area, Licor Bioscience, Inc. Lincoln, Nebraska, USA). The artificial saturated photosynthetic active radiation (PAR) was fixed at 1000 µmol m^{-2} s^{-1} and ambient carbon dioxide concentration (Ca) maintained at 400 µmol mol^{-1}. Measurements were taken in two-week interval on sunny days between 9h00 and 11h00. Yield were determined by the number of fruits and mass during the harvest. Number of fruits were determined by counting number of fruits in each plant representing a sample. On the other hand, fruit mass was measured by weighing individual fruit using calibrated bench top balanced weighing scale (WTB200, RADWAG. Poland).

4.3.5 Quality parameters

All quality parameters were measured during the harvest time. First harvest was conducted in week 12. All fruit in a truss from mature green to red were harvested and measured colour on the same day. Fruit colour was measured using Konica Minolta Chroma meter CR-300, INC, Japan (López Camelo and Gómez, 2004). Measurements were taken by scanning fruit on the equatorial region. Fruit colour measurements included lightness (L*), green to red (a*) and blue to yellow (b*) the results combined as the tomato Colour Index (Hobson et al., 1983) using Eq. 1

Colour index = $2000a \div LC$ 1

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

TA was measured using Mettler Toledo compact titrator G10S. *TA* was measured in each fruit per plant, per replicate, per treatment and taking the average mean of replicates. Briefly, samples were prepared by pipetting 8 mL of juice into a 100 mL beaker. Using another clean pippete tip, 42 mL distilled water was added to the juice in the beaker and titrated with 0.1M NaOH to a pH value of 8.1 using a Mettler Toledo. The acid was calculated as percentage of citric acid using a factor 0.0064, Eq. 2.

Percentage acid=$\frac{titre(mlNaOH)XACIDfactorX100}{8(mljuice)}$ 2

BrimA is an index used to measure the balance between acidity and sweetness was calculated using Eq. 3 as described by Jordan et al. (2001).

$BrimA = TSS - k\ (TA)$ 3

Where *k* is a constant that reflects the tongue's higher sensitivity to *TA* compared to *TSS*. The *k* allows *TSS* amounts higher than *TA* to make the same numerical change to *BrimA*. The equation of *BrimA* (Eq. 3) was adjusted as recommended by Obenland et al. (2009) who changed the value of constant (*k*) of 5 suggested by Jordan *et al*. (2001) with 3 and 4 in order to generate positive *BrimA* values for oranges.

4.3.6 Statistical analysis

The data collected were subjected to the two- way analysis of variance (ANOVA) using GenStat statistical software (GenStat1, 18.1 edition, VSN International, UK). Mean separation was conducted using Fischer's least significant difference (LSD) at 5% level of significance. The values of Standard error were calculated where a significant standard deviation was found at ($p < 0.05$) between individual values. Correlation analysis which measures the level of association among the analyzed parameters was performed using Microsoft excel windows (10)

4.4 Result

4.4.1 Effect of trellising methods on growth, photosynthesis and yield

Results for the present study reported significant differences ($p < 0.05$) in response to growth, photosynthesis and yield performance among the different trellising methods (Figs.1A-1E). Differences in photosynthetic rate (*A*) were slightly significant among the treatments ($p < 0.05$) with the late trellising method achieving the highest *A*, followed by early layering and lastly vertical trellising methods. *A* also varied significantly ($p < 0.01$) with time and the highest rate were observed in the early stages of development (3 – 10 weeks after transplanting) and declined significantly in all trellising methods from week 12 after transplanting onwards (Figs. 1A – 1E). The general trend was that the late trellising method was having a higher *A* in most cases as compared to early and vertical trellising methods. Similarly, plant height exhibited slight differences ($p < 0.05$) among the trellising methods where early and late layering method respectively showed increased plant height compared to vertical trellising method. On the other hand, significant differences were observed among plant height during the time of evaluation ($p < 0.01$) and the interaction of trellising methods and time ($p < 0.05$). Plants trellised with vertical trellising method had higher stem diameter (10.91 mm plant^{-1}) than early layering (10.40 mm plant^{-1}) and late layering trellising (10.33 mm plant^{-1}). Stem diameter also varied significantly ($p < 0.01$) in all the trellising methods during the time of evaluation. In terms of yield, the result showed variability ($p < 0.05$) with respect to number of fruits among different trellising methods. Early layering showed increased number of fruits (6.47 fruit plant^{-1}) followed by late layering (5.67 fruit plant^{-1}) with vertical trellising recording the least number of fruits (5.22 fruit plant^{-1}) (Fig.1D). On the other hand, the interaction between trellising method and harvesting time varied significantly ($p < 0.01$) with regard to the number of fruits during the harvesting period. The higher number of fruits harvested were observed during the 1st and 3rd harvest and the lowest number of fruits was observed in the 2nd harvest. Different trellising methods showed significant differences ($p < 0.05$) with regard to fruits mass. Similarly, plants trellised with early layering method showed increased fruit mass (132.2 g plant^{-1}) followed by late layering (131.2 g plant^{-1}) and lastly, vertical trellising method on evarage (123.2g plant^{-1}).

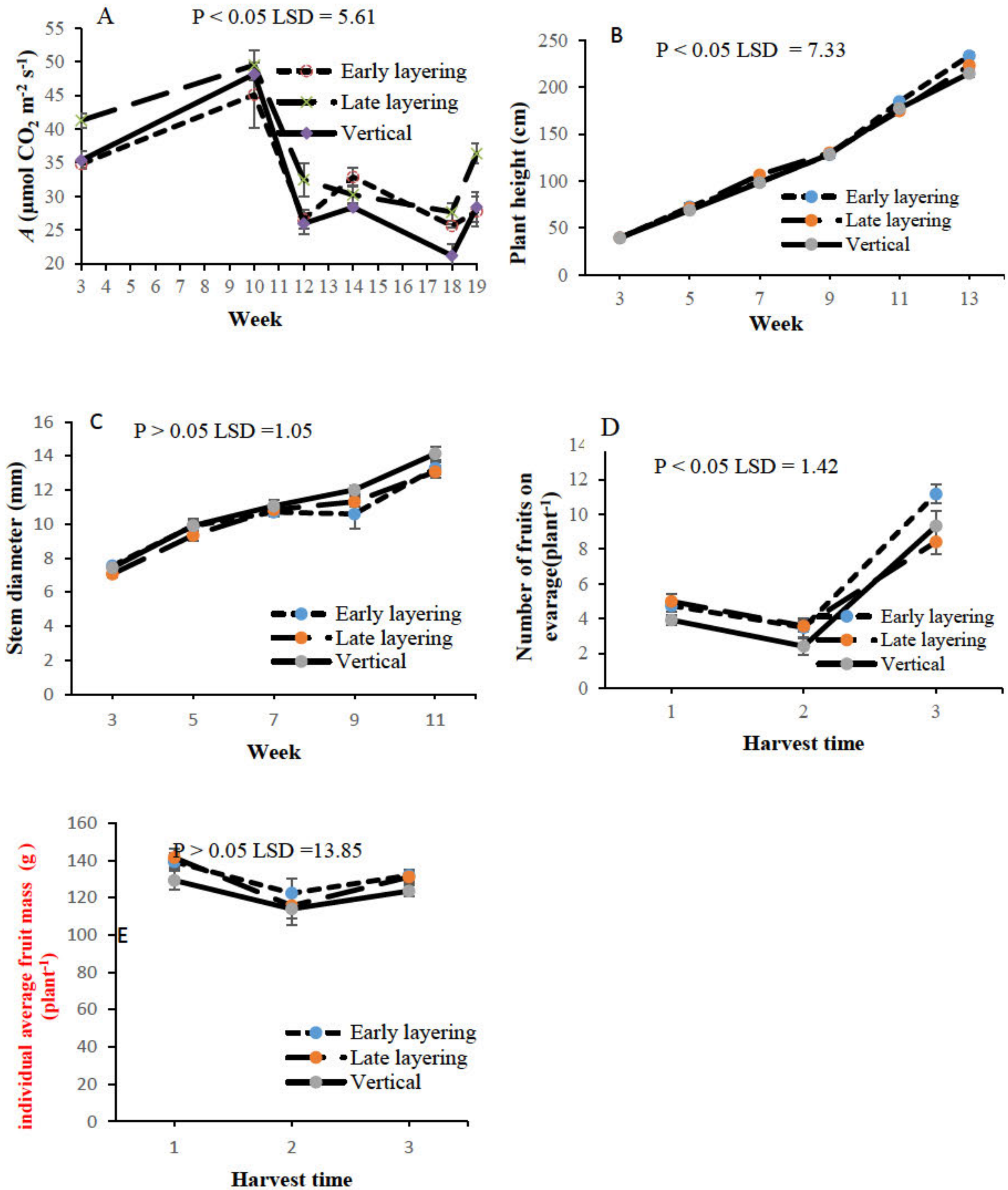
A
P < 0.05 LSD = 5.61
A (μmol CO2 m-2 s-1)
Week
Early layering
Late layering
Vertical
B
P < 0.05 LSD = 7.33
Plant height (cm)
Week
Early layering
Late layering
Vertical
C
P > 0.05 LSD =1.05
Stem diameter (mm)
Week
Early layering
Late layering
Vertical
D
P < 0.05 LSD = 1.42
Number of fruits on evarage(plant-1)
Harvest time
Early layering
Late layering
Vertical
E
P > 0.05 LSD =13.85
individual average fruit mass (g) (plant-1)
Harvest time
Early layering
Late layering
Vertical

Fig. 8: The effect of trellising methods on photosynthetic rate (A), Plant height (B), Stem diameter (C) Number of fruits (D) and Fruit mass (E) of indeterminate tomatoes produced in dome shape tunnels.

4.4.2 Effect of trellising methods on quality parameters

All quality parameters on average were not significantly different ($p > 0.05$) with respect to trellising methods, however, the interaction between trellising method and harvesting time were significantly different (Fig. 2A-2E). Significant difference ($p < 0.05$) was observed in colour index with fruits from the 1st and 2nd harvest being more ripen than the 3rd harvest in all the trellising methods. The general trend was that early layering and vertical trellising had higher colour index compared to late layering. *TSS* and *TA* showed no significant difference among different trellising methods (Fig. 2B-2C). On the other hand, *TSS* and *TA* varied significant during the sampling time. The trend of these parameters was inversely proportional to one another, increasing of *TSS* was the decrease of *TA* (Fig. 2B-2C). The current study showed no variation on *TSS/TA* and *BrimA* among trellising methods. However, harvest time influenced the variation in *Brim A* among the trellising methods with the 2nd harvest reporting the highest value.

Table 1: Fruit quality parameters on different trellising methods at different harvest time

Time	Trellising method	Colour index	*TSS*	*TA*	*TSS/TA*	*BrimA*
Harvest 1	**Early**	22.14cd	4.10bc	0.28abc	14.70a	2.69bc
	Late	11.98b	4.30cd	0.28abc	16.02ab	2.92cd
	Vertical	18.80bc	4.40d	0.30c	15.24ab	2.93cd
Harvest 2	**Early**	23.56cd	4.38cd	0.25ab	18.20bc	3.15d
	Late	22.86cd	4.39cd	0.25ab	18.13bc	3.14d
	Vertical	29.96d	4.39cd	0.24a	15.24ab	3.19d
Harvest 3	**Early**	-3.27a	3.69a	0.29bc	13.21a	2.25a
	Late	-5.30a	3.91ab	0.27abc	15.36ab	2.56abc
	Vertical	-8.51a	3.79ab	0.26abc	15.21ab	2.50ab
P- Value		0.047	0.459	0.34	0.78	0.72
LSD		7.23	0.30	0.04	2.78	0.35
CV %		13.5	0.8	1.7	1.5	0.5

Colour index, Total soluble solids (*TSS*), Titratable acids (*TA*), *BrimA,* early (early layering trellising), late (late layering trellising) and vertical (vertical trellising)

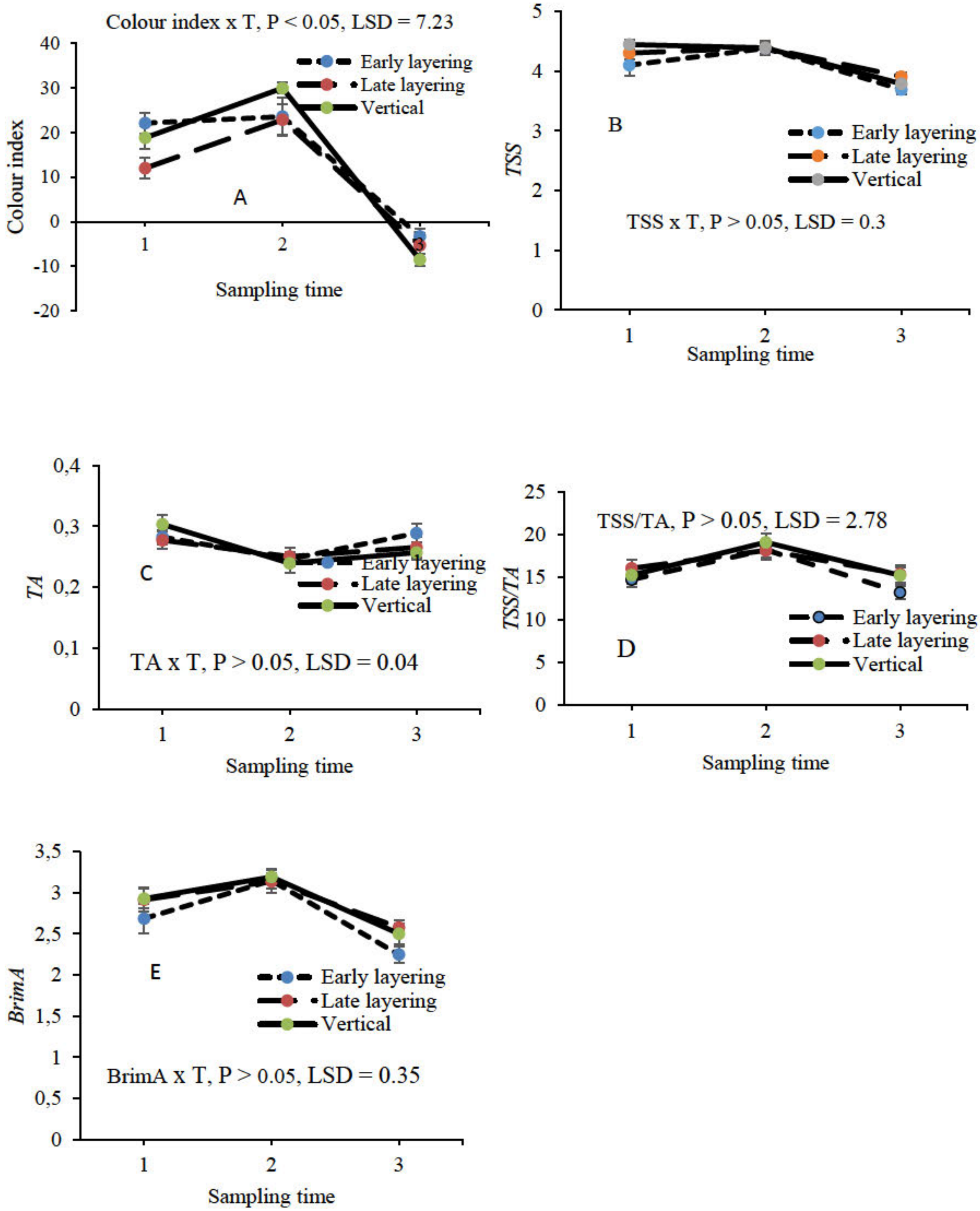
Colour index x T, P < 0.05, LSD = 7.23
Colour index
Early layering
Late layering
Vertical
A
Sampling time
40
30
20
10
0
-10
-20
1
2
3
B
TSS
Early layering
Late layering
Vertical
TSS x T, P > 0.05, LSD = 0.3
Sampling time
5
4
3
2
1
0
1
2
3
C
TA
Early layering
Late layering
Vertical
TA x T, P > 0.05, LSD = 0.04
Sampling time
0,4
0,3
0,2
0,1
0
1
2
3
TSS/TA, P > 0.05, LSD = 2.78
TSS/TA
Early layering
Late layering
Vertical
D
Sampling time
25
20
15
10
5
0
1
2
3
E
BrimA
Early layering
Late layering
Vertical
BrimA x T, P > 0.05, LSD = 0.35
Sampling time
3,5
3
2,5
2
1,5
1
0,5
0
1
2
3

Fig. 9: The effect of trellising methods on colour index (A), total soluble solids (B), titratable acids (C), total soluble solids/titratable acids (D) and BrimA (E) of tomatoes grown in dome shape tunnels.

4.4.3 Correlation amongst the measured parameters

The correlation coefficients describing the level of association between growth, physiological response and yield as well as quality parameters among different trellising methods are presented in Table 2. In the early layering trellising method, plant height was positively and significantly correlated with stem diameter (0.74; P < 0.05). Number of fruits also showed positive and significant correlation to *A* (0.67; P < 0.05) whereas negative and significant correlation was reported between colour and TSS (-0.63 and -0.82; P < 0.05) respectively. On the other hand, early layering showed positive and significant correlation between *A* and colour (0.74; P < 0.05). *TSS* also exhibited positive and significant correlation to colour (0.75; P < 0.05) and *BrimA* (0.87; P < 0.05).

Late layering trellising method showed positive and significant correlation between plant height and stem diameter (0.93; P < 0.01). Number of fruits showed positive and significant correlation with *A* (0.84; P < 0.05), however it showed a negative and significant correlation with colour (-0.73; P < 0.05) and *TSS* (-0.52; P > 0.05) on late layering trellising method. *A* exhibited positive and significant correlation to colour (0.69; P < 0.05), while positive and significant correlation was found between *TSS* and *BrimA* on late layering trellising method.

Vertical trellising method, plant height exhibited positive and significant correlation to stem diameter (0.85; P < 0.05). Number of fruits revealed a positive and significant correlation to *A* (0.72; P < 0.05), whereas negative and significant correlation was reported with regard to colour and TSS (-0.77 and -0.62; P < 0.05) respectively. Positive and significant correlation between *A* and colour (0.80; P < 0.05) was observed among vertical trellising method. On the other hand, *TSS* showed positive and significant correlation to colour (0.63; P < 0.05) and *BrimA* (0.85; P < 0.05).

Table 2: Correlation amongst the plant growth, physiological response, and yield and quality parameters

	Early layering		Late layering		Vertical	
Parameter	P value	r	P value	r	P value	r
Plant height vs stem diameter	P < 0.05	0.74	P < 0.01	0.93	P < 0.05	0.85
Number of fruits Vs *A*	P < 0.05	0.67	P < 0.05	0.84	P < 0.05	0.72
Number of fruits Vs colour	P < 0.05	-0.63	P < 0.05	-0.73	P < 0.05	-0.77
Number of fruits Vs *TSS*	P < 0.05	-0.82	P > 0.05	-0.52	P < 0.05	-0.62
A vs colour	P < 0.05	0.74	P < 0.05	0.69	P < 0.05	0.8
Colour vs *TSS*	P < 0.05	0.75	P > 0.05	0.47	P < 0.05	0.63
TSS vs *BrimA*	P < 0.05	0.87	P < 0.05	0.78	P < 0.05	0.85

4.5 Discussion

The aim of the present study was to evaluate the time effect of layering trellising methods on growth and yield performance of indeterminate tomato cultivars normally grown under dome shape tunnels. Results from this study showed that late layering and early layering had higher A than vertical trellising. The increase in A can be attributed to the high accumulation of high photosynthates by the plants in late layering and early layering treatment. The results also showed increased A for all the trellising methods after transplanting and decline later until the end of evaluation. The decline in A from week 12 was assumed to be caused by the change in weather conditions, since the season was changing from summer to autumn. Early and late layering had a slightly high plant height and low stem diameter compared to vertical trellising method. These findings reveal that vertical trellising at late stage of growth had reached the maximum level of the tunnel and got exposed to high temperatures. Therefore, heat stress causes water loss in the epical meristem and impair membrane integrity, thus resulting to decrease in photosynthetic pigments, photosynthetic rate and growth (Ahammed et al., 2018). Similar results were found by Camejo et al. (2005), who investigated effect of high temperature on photosynthetic activity of tomato cultivar (Campbell-28) . On the other hand, the interaction between trellising methods and time showed significant differences among the plants height with vertical and late layering trellising methods increasing in a similar pattern until week 11. Late layering had showed slight increase after a change in growing position due to layering. These results further confirm that vertical trellising inhibits normal growth of the plants when plants are allowed to reach maximum level of the tunnel. High temperature causes inhibition of photosystem II (PSII) activity, thus resulting to decrease in chlorophyll fluorescence (Lu et al., 2017). Calvin cycle activity is very sensitive to heat stress and lead to inhibition photosynthesis through the reduction of ribulose-1,5-bisphosphate (RuBP) supply caused by low ATP synthesis (Tezara et al., 1999). The current study showed increased fruit number and mass per plant for early and late layering trellising compared to vertical trellising. This is evident that the yield of the plant depends on the performance of the plant during growth, as the present study exhibited high *A* and plant height in early and late layering. Correlation co-efficient also showed positive correlation between number of fruit and *A* which further confirm the dependency of yield on photosynthesis. Number of fruit varied significant among harvest time where higher fruit number was observed during 3rd and 1st harvest. This increase was influenced by the balance between the source and the sink strength. Fruits harvested during the 1st harvest were mostly those that developed and grew earlier when the plant experienced less competition of assimilates, while the fruits harvested during the 3rd harvest developed at a later stage after all the lower fruits trusses were already harvested.

Furthermore, the current study showed significant differences with respect to colour index in relation to harvesting time. Higher colour index was observed in the 1st and 2nd harvest, meaning that fruits harvested were more ripen. Correlation co-efficient revealed that colour index of the fruits were significantly and negatively correlated with the number of the fruits, meaning that plant with high number of fruit had low colour index. High number of fruit in the truss decrease the amount of light receive by the fruit because fruits get shaded one another. Skin colour of the fruit results from pigments, high light received by the fruits decrease chlorophyll content of the fruit and increase the formation of carotenoids and lycopene (Lancaster et al., 1997; Gautier et al., 2005). In contrast, the observed results showed non-significant differences for *TSS* and *TA*, and their concentration changed with harvesting time. In addition, the observed results showed that plants harvested with the high number of fruits obtained lower *TSS*. The lack of correlation between *TSS* and fruit number might be associated with high sink strength which stimulate the utilization of photosynthates. Furthermore, a negative correlation was reported between *TA* and *TSS*, suggesting that these variables are inversely proportional to one another. On the contrary, positive associations were reported between *TSS* and colour index which attributes that ripe fruits have high concentration of total soluble solids. *BrimA* which measures the balance between Brix (sweetness) and acidity (sourness) (Jordan et al., 2001; McDonald et al., 2013). The present study exhibited non-significant differences with respect to *BrimA* among treatments, suggesting no variation among the different trellising methods. *BrimA* varied significant during the sampling time where higher *BrimA* was observed in the 2nd harvest, meaning that fruits harvested had more flavor than 1st and 3rd harvest. Correlation co-efficient also found positive and significant correlation between *TSS* and *BrimA*. The trend further confirms the relationship between *BrimA* and *TSS* where these variables were increasing and decreasing with a similar trend. *TSS/ TA* ratio used as a maturity index of tomato fruit, however measurement does not always correlate well with the perception of the fruit taste (Magwaza and Opara, 2015). One challenge is that the same ratio maybe derived from different concentrations of *TA* and *TSS*, resulting to different flavor perceptions for the same ratio. The 2nd problem is that *TSS* depends on the size of fruit (Beckles, 2012). Present study reported non-significant different with *TSS/TA* among trellising methods. *TSS/TA* varied significantly with respect to sampling time where higher *TSS/TA* was observed in the 2nd sampling time. These findings showed that TSS/TA was directly proportional to TSS as these parameters increased and decreased with a similar trend.

4.6 Conclusion

The study found that trellising methods had an impact on growth, photosynthetic efficiency and yield of tomato produce in dome shape tunnels. Early and late layering trellising methods showed high photosynthetic rate, fruit number and fruit mass than vertical trellising. This suggests that both early and late layering can be used as a good trellising method in dome shape tunnels. The poor performance of vertical trellising on photosynthetic rate and yield over early and late layering lies to the fact that vertical trellising method at late stage got expose to high temperature. Therefore, high temperature cause water loss in the leaves of epical meristem and disintegration of membrane, resulting to decrease in photosynthesis and yield. Thus, further research focusing on trellising methods during winter months is required.

4.7 References

Ahammed, G.J., Xu, W., Liu, A. & Chen, S. 2018. COMT1 silencing aggravates heat stress-induced reduction in photosynthesis by decreasing chlorophyll content, photosystem II activity, and electron transport efficiency in tomato. Frontiers in Plant Science, 9**,** 998.

Alam, M., Islam, N., Ahmad, S., Hossen, M. & Islam, M. 2016. Effect of different staking methods and stem pruning on yield and quality of summer tomato. Bangladesh Journal of Agricultural Research, 41**,** 419-432.

Camejo, D., Rodríguez, P., Morales, M.A., Dell'Amico, J.M., Torrecillas, A. & Alarcón, J. J. 2005. High temperature effects on photosynthetic activity of two tomato cultivars with different heat susceptibility. Journal of plant physiology, 162**,** 281-289.

FAO. 2013. Food and Agriculture Organization (FAO) of the United Nations. Production quantities of tomato in the world. http://www.fao.org/faostat/en/#data/QC/visualize. Last accessed 20 september 2018.

FAO. 2019. Food and Agriculture Organization (FAO) of the United Nations. The state of food security and nutrition in the world 2019: safeguarding against economic slowdowns and downturns.

Gautier, H., Rocci, A., Buret, M., Grasselly, D. & Causse, M. 2005. Fruit load or fruit position alters response to temperature and subsequently cherry tomato quality. Journal of the Science of Food and Agriculture, 85**,** 1009-1016.

Heuvelink, E. 2005. Tomatoes, CABI, p.258-276

Hobson, G.E., Adams, P. & Dixon, T.J. 1983. Assessing the colour of tomato fruit during ripening. Journal of the Science of Food and Agriculture, 34**,** 286-292.

Jordan, R.B., Seelye, R.J. & McGlone, V.A. 2001. A sensory-based alternative to brix/acid ratio. Food technology (Chicago), 55**,** 36-44.

Kim, S.H., Shackel., K.A. & Lieth, J.H. 2004. Bending alters water balance and reduces photosynthesis of rose shoots. Journal of the American Society for Horticultural Science, 129**,** 896-901.

Lancaster, J.E., Lister, C.E., Reay, P.F. & Triggs, C.M. 1997. Influence of pigment composition on skin color in a wide range of fruit and vegetables. Journal of the American Society for Horticultural Science, 122**,** 594-598.

Lecuona, A. 2013. Trellising tomato plants in a greenhouse. https://www.commercial-hydroponic-farming.com/trellising-tomato-plants/. Last accessed: 20 May 2019.

López Camelo, A.F. & Gómez, P.A. 2004. Comparison of color indexes for tomato ripening. Horticultura Brasileira, 22, 534-537.

Lu, T., Meng, Z., Zhang, G., Qi, M., Sun, Z., Liu, Y. & Li, T. 2017. Sub-high temperature and high light intensity induced irreversible inhibition on photosynthesis system of tomato plant (*Solanum lycopersicum L*.). Frontiers in plant science, 8, 365.

Magwaza, L.S. & Opara, U.L. 2015. Analytical methods for determination of sugars and sweetness of horticultural products—A review. Scientia Horticulturae, 184, 179-192.

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 biology and technology, 86, 91-99.

Mitchell, B.A., Uchanski, M.E. & Elliott, A. 2019. Fruit cluster pruning of tomato in an organic high-tunnel system. Horticultural Science, 54, 311-316.

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*). Journal of Food Engineering, 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 Biology and Technology, 52, 156-163.

Owen, W.G., Hilligoss, A. & Lopez, R.G. 2016. Late-season High Tunnel Planting of Specialty Cut Flowers in the Midwestern United States Influences Yield and Stem Quality. Horticultural Technology, 26, 338-343.

Reynolds, A.G. & Heuvel, J.E.V. 2009. Influence of grapevine training systems on vine growth and fruit composition: a review. American Journal of Enology and Viticulture, 60, 251-268.

Tezara, W., Mitchell, V., Driscoll, S. & Lawlor, D. 1999. Water stress inhibits plant photosynthesis by decreasing coupling factor and ATP. Nature, 401, 914.

Chapter 5: Effects of stem training on physiology, growth, and yield responses of indeterminate tomato (*Solanum lycopersicum*) plants grown in protected cultivation

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5.1 Abstract

The lower yield of tomatoes grown in tunnels remains a challenge due to the limited space. Stem training has long been identified as one of the most important horticultural practices used to improve yield and fruit quality of tomatoes grown in commercial tunnels, however, there is little information available for dome shape tunnels used particularly by smallholder farmers. The common stem training methods used in tunnels include single stem (SS), double stem (DS) and two plants per pot (TPP), and, their effect on growth, development and plant physiology significantly varies, hence affecting crop productivity. This study evaluated the effect of stem training on physiology, growth, and yield responses of indeterminate tomato grown in a polyethylene tunnel. The experiment was conducted in the 8 m x 30 m dome shape tunnel using a complete randomized design with different training methods as a treatment factor consisting of three levels, namely, SS, DS and TPP. Physiological and growth parameters' data were collected during week 3, week 10, week 12, week 14 and week 18. Each level was replicated 3 times with each replication consisting of 4 plants, resulting in 36 experimental units (3 x 3 x 4). The observed results showed significant differences among the stem training methods with regard to leaf gas exchange, the yield and fruit quality parameters. The results on the photosynthetic rate (*A*) and stomatal conductance (*gs*) were significantly different ($P < 0.05$). A higher photosynthetic rate was observed on a single stem (49.04 μmol CO_2 m^{-2} s^{-2}) followed by the double stem training (1.54 mol m^{-2}). Similarly, SS and DS showed increased growth, yield and fruit quality parameters. SS showed increased plant height (126 cm), stem diameter (11.2 cm) and evarage of individual fruit mass (138 g). However, DS and TPP on average exhibited higher number of fruit per havest (7.11 and 6.64 per plant), colour index (14.4 and 17.0), *TSS* (4.45 and 4.33), *TA* (0.265 and 0.267) and

Brima (2.67 and 2.60) than SS treatment (number of fruit (5.3), colour index (11.3), *TSS* (4.09) *TA* (0.23) and *BrimA* (2.46)). The results obtained from this study demonstrated the effect of training method on growth, yield and physiological performance of tomatoes grown in tunnels. However, further research that focuses on stem training among different cultivars is still needed.

Keywords: Stem training; gas exchange; indeterminate tomato; growth; yield

5.2 Introduction

Tomato production 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 of limited resources, such as poor soils and shortage of land. Producing high yield and good quality of this crop in an open field is very challenging due to unfavorable environmental conditions and a high incidence of pests and diseases. However, the planting of tomatoes under protected cultivation provides a certain degree of control and allows farmers to produce even when the crop is out of season because it is easier to control temperature under such systems.

Despite the widespread adoption of protected cultivation, the use of such systems remains a challenge, including reduced yield and difficulty of the plant to grow upright due to limited height which is provided by the dome shape tunnel. The yield of tomato in 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 aiming at improving yield by enhancing fruit number, size as well as quality (Maboko and Plooy, 2008) have been developed. This includes horticultural practices such as fruit thinning, management of plant population, cultivar selection and stem training (Maboko and Plooy, 2008). Stem training has been identified as one of the most important horticultural practices used to increase yield and improve fruit quality (Ara et al., 2007). Stem training is defined as the number of stems allowed to grow as a leader during plant growth. There are different types of stem training methods used for tomato production in tunnels and this includes; single stem, two plants per pot and double stem. Single stem training is achieved by removing all sucker stem to allow plants to grow as a single leader. Two plants per pot stem training method is achieved by planting two seedlings in one pot while removing all sucker stems to allow each seedling to grow as a single stem. On the other hand, double stem training is achieved by leaving sucker at the bottom to grow as the second main stem resulting to double leader stems growing.

Stem training methods have a different impact on plant physiology as well as yield. Different stem training methods may exhibit different leaf area index, and percentage of leaves exposed to sunlight. In addition, stem training also impacts the root density of tomato plants, for example, a method of growing two plants per pot at a later stage form root balls and also reduce light interception leading to down-regulation of photosynthetic capacity (Shi et al., 2008). Furthermore, the stem training method may also impact other numerous variables such as water use efficiency, transpiration and fruit formation.

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

Growing tomatoes as a double stem has been identified as an alternative method that can increase yield and reduce production cost compared to two plants per pot method because maintenance costs are similar (Amundson et al., 2012). Alam et al. (2016) found that tomato of BARI hybrid produced with double stem had high fruit mass compared to a single stem. Maboko et al. (2011) reported that tomato (FA593) produced in a double stem method had high yield and a high number of marketable fruit compared to a single stem. Similarly, Amundson et al. (2012) found that the two plants per pot method had a high yield of tomato during summer compared to a double stem method, whereas, there was no significant difference in winter. The findings reported by these authors necessitate more research since there is no clear information or consensus on yield of two plants per pot stem training compared to double stem training. Thus, the study aims at identifying the best stem training method that can increase yield and improve quality at the same time providing information on the horticultural performance of these training methods

5.3 Materials and methods

5.3.1 Plant material

Seedlings were purchased from a local commercial nursery (Sunshine Seedlings®, Pietermaritzburg, South Africa). The tomato seedlings used in this study were hybrid cultivar STAR 9037 (Starke Ayres seeds, Pietermaritzburg, South Africa). Seedlings were transplanted into 8 L bags filled with fine pine sawdust as a growing medium purchased from local sawmill (Glenside sawmill, Dalton, South Africa).

5.3.2 Controlled environmental condition

The study was conducted in the 8 m x 30 m dome-shaped tunnel structure covered with polyethylene plastic, in summer months between November 2018 and April 2019. The tunnel structure was located at Ukulinga Research Farm of the University of KwaZulu-Natal, South Africa (29°40'05.7"S 30°24'20.9"E). The temperature and relative humidity (RH) recorded during the plant growing period were respectively at an average of 38 °C and 41%.

5.3.3 Experimental design and cultivation procedures

The experiment was conducted using a complete randomized design consisting of stem training methods at three levels, namely, single stem, double stem and two plants per pot training methods. Each level was replicated 3 times with each replication consisting of 4 plants, resulting in 36 experimental units (3 x 3 x 4). Six weeks old seedlings were used and transplanted into 8 L bags filled with fine pine sawdust as a growing medium. The single stem (SS) training method was achieved by planting one seedling in a pot and removing all sucker stem as the plant grow, to allow plants to grow as a single leader. On the other hand, two plants per pot (TPP) method was achieved by planting two seedlings in one pot and remove all sucker stem to allow each seedling to grow as a single stem. Plants assigned to double stem (DS) were achieved by planting one seedling in a pot and allow the sucker at the bottom to grow as the second main stem resulting to double leader stems growing. Water-soluble inorganic fertilizer mix (commercial fertilizer) in the form of Solucal® (calcium nitrate), Multi-K (potassium nitrate) and Hygroponic® (ammonium nitrate with all essential micronutrients and macronutrients) was dissolved in one tank filled with 5000 L of water. Fertilizers were mixed according to the recommended rate for tunnel production by the manufacturer (Hygrotech SA, Pietermaritzburg, South Africa). A 2.7 kg Solucal, 500 g multi-K® and 3 kg Hygroponic® was mixed with water in a 5000 L tank from transplant to third flower. After the third flower truss to the end, fertilizers were increased by mixing 5000 L of water with 3.5 kg Solucal®, 1 kg Multi-K® and 5 kg Hygroponic®.

5.3.4 Data collection

5.3.4.1 Measurement of leaf gaseous exchange parameters

Leaf gas exchange was measured on Week 3, 10, 12, 14, 18 after planting, using Portable Photosynthesis System LI-6400 XT (Licor Bioscience, Inc. Lincoln, Nebraska, USA) fitted with infrared gas analyzer connected to a leaf chamber fluorimeter (LCF) (6400-40B, 2 cm^2 leaf area, Licor Bioscience, Inc. Lincoln, Nebraska, USA). The artificial saturated photosynthetic active radiation (PAR) and external CO_2 were fixed at 1000 µmol m^{-2} s^{-1} and 400 µmol mol^{-1}, respectively. The measurements were taken at two weeks' intervals on sunny days between 11h00 and 13h00. Sampling was taken in the apex of one leaf of each plant representing a replicate. Leaf gaseous exchange parameters such as photosynthetic rate (*A*), stomatal conductance (*gs*), transpiration rate (*T*), intercellular CO_2 concentration (*Ci*) and the ratio of intercellular and atmospheric CO_2 (*Ci/Ca*) concentration were measured. The stomatal limitation was calculated as 1-*Ci/Ca* (Dong et al., 2016). Water use efficiency (*WUE*) was calculated as the ratio of *A* and *T* (Mashilo et al., 2017).

5.3.4.2 Plant growth parameters and yield

Plant height was measured on a 2-week interval, using a measuring tape. Measurements were taken from the base up to the apical point of the plant. Samples were taken in was made in each replicate of all the treatments. Stem diameter was measured using a caliper. Measurements were taken at the base of the stem in each plant representing a replicate. The yield of tomato was determined by the number of fruit harvested and mass measured. Fruit sampling for yield and quality measurement was taken on three sampling dates denoted as Harvest 1, 2 and 3. The number of fruit was determined by counting. On the other hand, fruit mass was determined by weighing individually fruit using a calibrated benchtop balanced weighing scale (WTB200, RADWAG. Poland). The sum of all fruit harvested and mass was used to estimate total yield.

5.3.4.3 Total soluble solids (*TSS*) and Titratable acid (*TA*)

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

TA was measured using 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 distilled water was added to the juice in the beaker and titrated with 0.1M NaOH to a pH value of 8.1 using a Mettler Toledo. The acid was calculated as the percentage of citric acid using a factor 0.0064, Eq. 1.

$$\text{Percentage acid}=\frac{titre(mlNaOH)XACIDfactorX100}{8(mljuice)} \qquad 1$$

TA was measured in each fruit per plant, per replicate, per treatment and taking the average mean of replicates.

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

$$BrimA = TSS - k\ (TA) \qquad 2$$

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

5.3.4.4 Fruit colour

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

Colour index = $2000a \div LC$

5.3.5 Statistical analysis

The collected data of measured variables were subjected to the analysis of variance (ANOVA) using statistical software GenStat (GenStat1, 18.1 edition, VSN International, UK). Mean was separated using Fischer's least significant difference (LSD) at 5% level of significance. The values of Standard error were calculated where a significant standard deviation was found at ($p < 0.05$)

between individual values. Pearson's correlation analysis was performed to describe the pattern of relationship between plant growth and leaf gas exchange parameters using Excel window's 10. Significance tests of the correlation coefficients were determined using excel window's 10.

5.4 Results

5.4.1 Leaf gas exchange in response to different stem training methods

Results on leaf gas exchange parameters reported slight differences ($P < 0.05$) among the stem training methods and their performance varied as time progressed (Table.1). Leaf photosynthetic rate (*A*) had no significant differences for all the stem training methods except for week 12, where single SS exhibited the highest *A* (49.56 µmol CO_2 m^{-2} s^{-2}) than the DS (36.34 µmol CO_2 m^{-2} s^{-2}) and TPP (39.53 µmol CO_2 m^{-2} s^{-2}) training method. Generally, *A* showed an increased performance during week 3 until week 10 and then declined until the end of the evaluation (Fig.1A). The interaction between the stem training methods was also significantly different ($P < 0.05$) in *A* with the highest value recorded by a single stem training method at 12 weeks after transplanting, (49.56). Significant effect ($P < 0.01$) was also observed in stomatal conductance (*gs)* (Table 1). Higher stomatal conductance (*gs*) was observed in single stem (-1.297 mmol m^{-2} s^{-1}) and double stem (-1.384 mmol m^{-2} $s^{-}1$) compared to two plants per pot (-1.648 mmol m^{-2} s^{-1}) for all the evaluation times except for week 3 which reported no significant differences (Table. 1). Variability in *gs* was also observed between the time of evaluation and interaction of stem training methods x time. Different stem training methods exhibited no significant difference ($p > 0.05$) in *Ci, Ci/Ca,* 1-*Ci/Ca, T* and *WUE*. However, *Ci, Ci/Ca* and 1- *Ci/Ca* varied significantly ($p < 0.01$) concerning time and interaction of stem training and time.

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	-1.384e	446.1f	1.21f	-0.21a	12.7a
	SS	72.42c	-1.297e	454.5f	1.23f	-0.23a	14.56
	TPP	67.76c	-1.648d	431e	1.16e	-0.16b	12.63a
Week 12	*DS*	36.34a	-2.002c	410.9cd	1.07c	-0.07d	16.2abc
	SS	49.56b	-1.85c	417.9d	1.11d	-0.11c	16.82abc
	TPP	39.53a	-2.204b	408.6cd	1.07c	-0.07d	13.35ab
Week 14	*DS*	35.73a	-2.37ab	405.5cd	1.06c	-0.06d	16.44abc
	SS	35.71a	-2.375ab	405.2cd	1.06c	-0.06d	16abc
	TPP	35.08a	-2.454a	404.3c	1.05c	-0.05d	15.15abc
Week 18	*DS*	39.91a	-2.396a	405.8cd	1.06c	-0.06d	14.12abc
	SS	40.07a	-2.314ab	406.8cd	1.07c	-0.07d	16.47abc
	TPP	37.48a	-2.336ab	406.6cd	1.06c	-0.06d	18.64abc
LSD		6.06	0.17	11.53	0.03	0.03	5.99

A**: photosynthetic rate (µmol CO_2 m^{-2} s^{-1}),** ***gs*****: stomatal conductance (mmol CO_2 m^{-2} s^{-1}),** ***Ci*****: intercellular CO_2 concentration (µmol mol^{-1}),** ***Ci/Ca*****: ratio of intercellular and atmospheric CO_2 concentration, 1-*****Ci/Ca*****: stomatal limitation,** ***T*****: transpiration rate (mmol H_2O m^{-2} s^{-1}),**

DS**: Double stem,** ***SS*****: Single stem and** ***TPP*****: Two plants per pot**

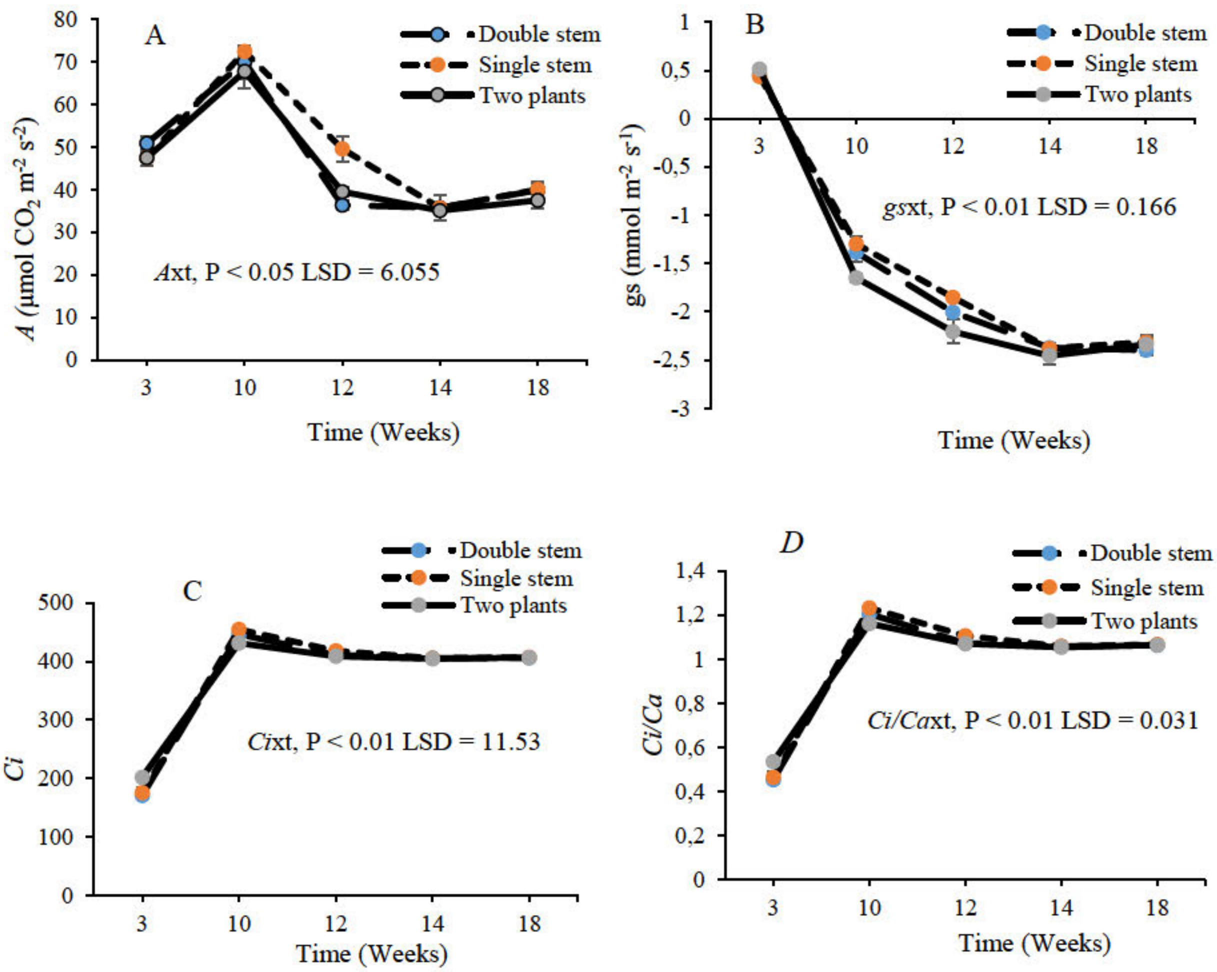

Fig. 10: Responses of leaf gas exchange parameters to different stem training methods. Photosynthetic rate (A), Stomatal conductance (B), Intercellular CO_2 concentration (C), Ratio of intercellular and atmospheric CO_2 concentration (D).

5.4.2 Plant growth parameters and yield responses to different stem training methods

Significant differences ($P < 0.05$) were observed among tested growth and yield parameters indicating variability in responses of tomato plants under different stem training methods. Single stem training method plants showed increased plant height than double stem and two plants per pot training methods (Fig. 2A). The interaction between training method and time was also significantly different, with single stem training showing an average mean of 126 cm than double stem and two plants per pot training (114 cm and 114 cm), respectively. The highest plant height was observed in week 13 in all the treatments. In terms of stem diameter, significant differences ($P < 0.05$) were observed among the stem training methods. The bigger stem diameter was recorded in a single stem method (11.2 mm) compared to two plants per pot method (9.97 mm) and double stem method (9.55 mm) (Fig. 2B). Stem diameter also showed positive ($P < 0.05$) interaction between stem training method and time, where the thickness of single (12.2mm) and double stem training methods (10.04 mm) increased significantly in week 7 after transplanting.

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

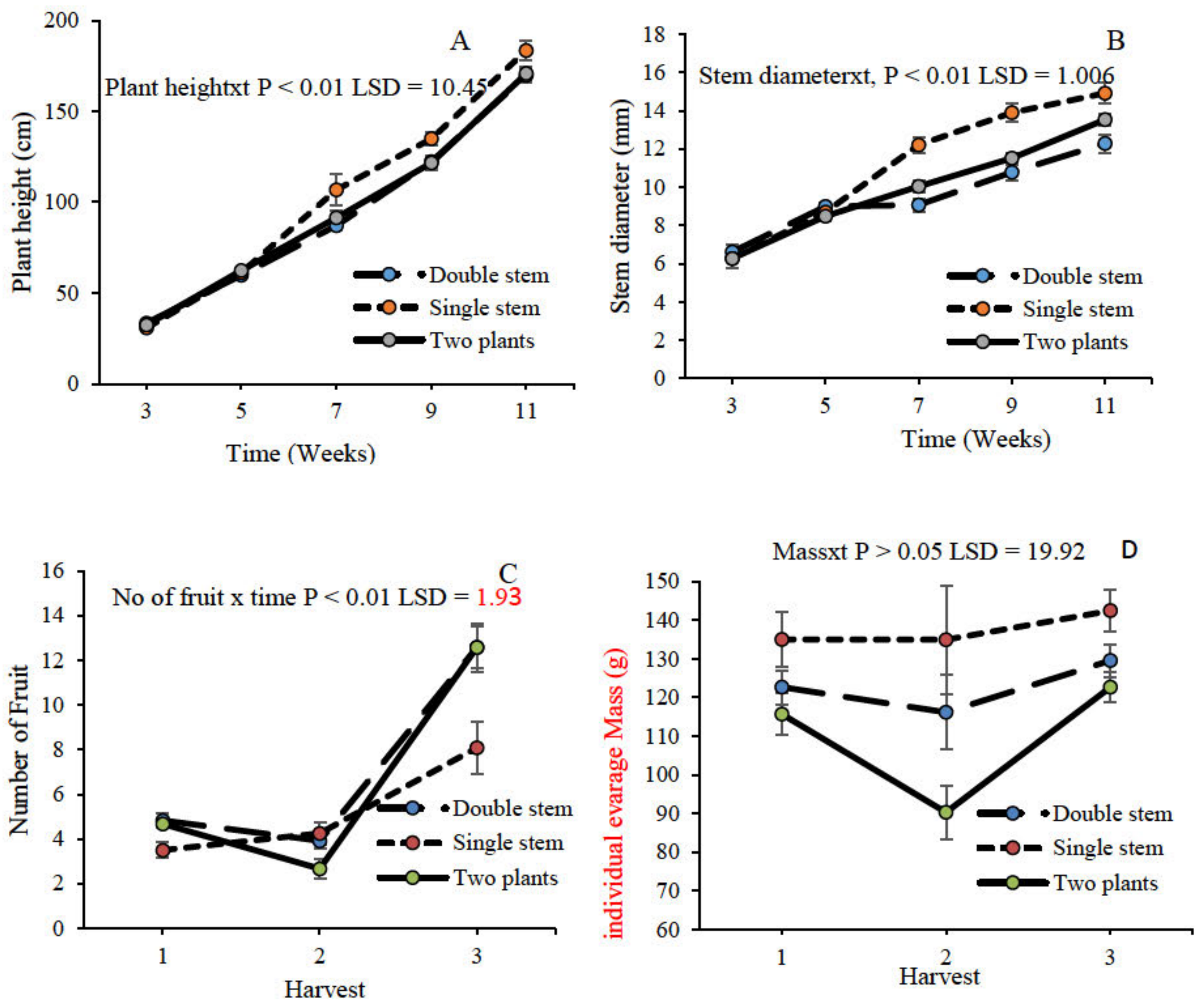

Fig. 11: Effect of different stem training methods on growth and yield of indeterminate tomato produce in dome shape tunnels. Plant height (A), Stem diameter (B), Number of fruit (C) and Fruit mass (D).

5.4.3 Tomato fruit quality in response to different stem training methods

The results showed that the interaction of stem training and time with respect to colour index was significant different ($P < 0.01$) (Table 2). The general trend was that double and two plants per pot was found to have higher colour index in most cases as compare to single stem. Colour index varied significant (P < 0.05) with time of sampling where the increase was observed in the 1st and 2nd harvest and decline in 3rd harvest in all treatments (Fig. 3A). The results showed that *TSS* was significantly higher (P < 0.05) in double stem and two plants per pot training methods than a single stem, respectively (Table 2). The *TSS* was observed to decline with time in all the training methods (Fig 3A). Similar trends were observed in *TA* in all training methods where single stem training methods had a significant lower *TA* than two plants per pot and double stem training methods (Table 3) while also the *TA* was found to decrease with time (Fig. 3C). Lower *BrimA* was observed also in a single stem training method which had a value of 2.46 compared to 2.60 and 2.67 in two plants per pot and a double stem training method (Table 2), respectively. *BrimA* was also observed to decrease with time where a single stem training method was lower than other treatments (Fig. 3D).

Table 2: Fruit quality parameters on different stem training methods

Time	**Treatment**	**Colour index**	***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

Colour index, Total soluble solids (*TSS*), Titratable acids (*TA*) and BrimA

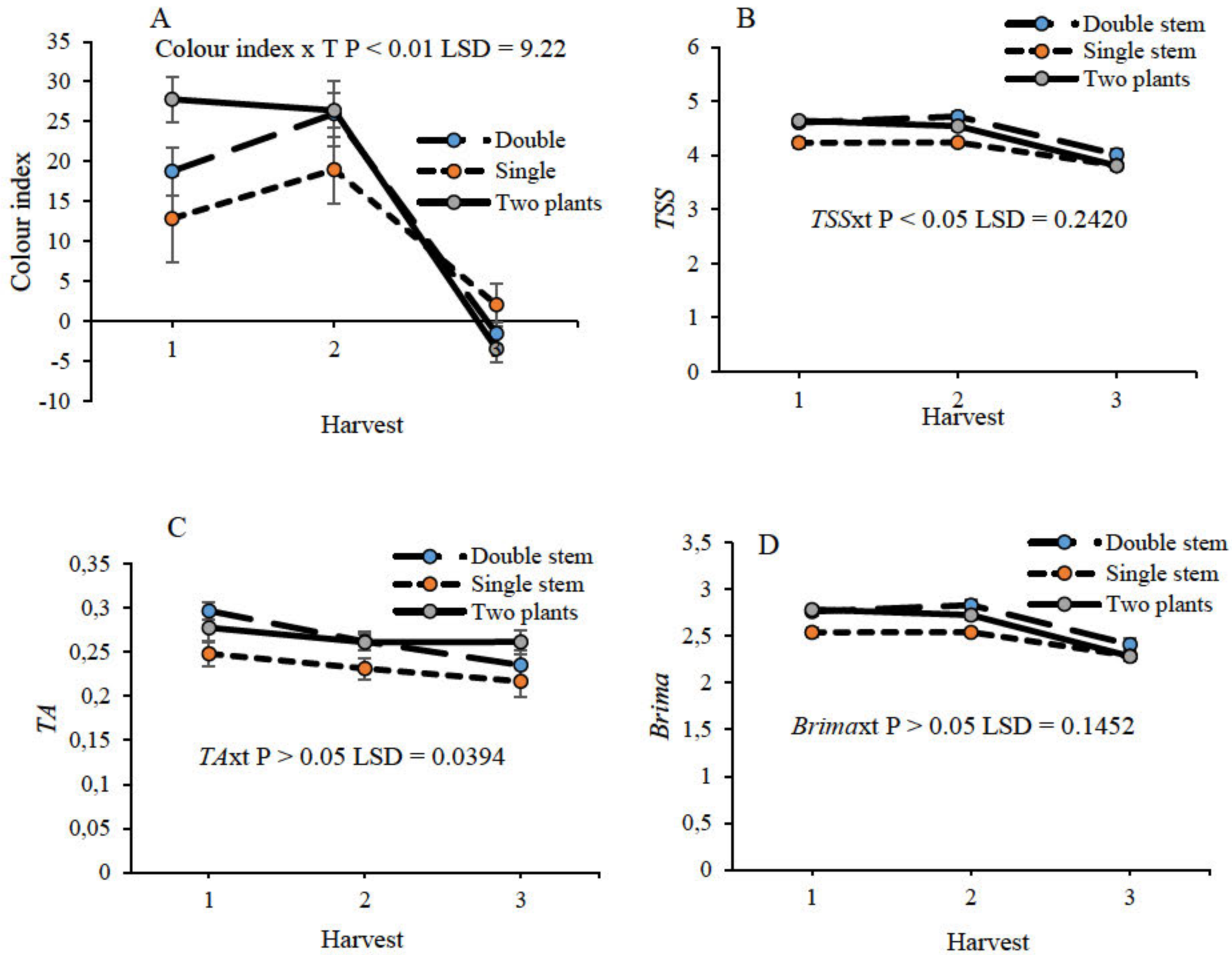

Fig. 12: Quality parameters in response to different stem training methods in different harvest times. Colour index (A), Total soluble solids (B), Titratable acids (C) and *Brima* (D)

5.4.4 The correlation amongst the plant growth and leaf gas exchange parameters

The correlation coefficients showing the level of association between plant growth and leaf gas exchange parameters tested among different stem training methods are presented in Table 4. In a single stem method, plant height was positive and significantly correlated to *Ci* (0.80; $P < 0.01$), *Ci/Ca* (0.79; $P < 0.01$) but negatively correlated to *gs* (-0.90; $P < 0.01$) and 1-*Ci/Ca* (-0.79; $P < 0.01$). Single stem training method results also revealed a negative and non-significant correlation between plant height and *A* (-0.56; $P > 0.05$). Stem diameter positively and significantly correlated to *Ci* (0.85; $P < 0.01$), *Ci/Ca* (0.85; $P < 0.01$) but negatively and significantly correlated to *gs* (-0.92; $P < 0.01$) and 1-*Ci/Ca* (-0.85; $P < 0.01$) under single stem method.

In terms of two plants per pot training methods, plant height exhibited a positive and significant correlation to *Ci* (0.77; $P < 0.01$) and *Ci/Ca* (0.77; $P < 0.01$). On the other hand, plant height negatively and significantly correlated to *A* (-0.74; $P < 0.01$), *gs* (-0.79; $P < 0.01$) and 1-*Ci/Ca* (-0.77; $P < 0.01$). Stem diameter positively and significantly correlated to *Ci* (0.86; $P < 0.01$), *Ci/Ca* (0.86; $P < 0.01$) under two plants per pot training method. However, stem diameter negatively and significantly correlated with *A* (-0.65; $P < 0.05$), *gs* (-0.88; $P < 0.01$) and 1-*Ci/Ca* (-0.86; $P < 0.01$) under two plants per pot.

Double stem training method revealed that plant height was positively and significantly correlated with *Ci* (0.80; $P < 0.01$), *Ci/Ca* (0.80; $P < 0.01$) but negatively and significantly correlated to *A* (-0.60; $P < 0.05$), *gs* (-0.88; $P < 0.01$) and 1-*Ci/Ca* (-0.80; $P < 0.01$). Stem diameter positively and significantly correlated to *Ci* (0.65; $P < 0.05$), *Ci/Ca* (0.65; $P < 0.05$) whereas negatively and significantly correlated with *gs* (-0.70; $P < 0.05$), 1-*Ci/Ca* (-0.65; $P < 0.05$) under double stem method.

Table 4: Correlation coefficients of leaf gas exchange and plant growth parameters in different stem training methods

	Single stem		Two plants per pot		Double stem	
Parameter	P-value	r	P-value	r	P-value	r
Plant Height *vs Ci*	P < 0.01	0.8	P < 0.01	0.77	P < 0.01	0.8
Plant Height *vs Ci/Ca*	P < 0.01	0.79	P < 0.01	0.77	P < 0.01	0.8
Plant Height *vs gs*	P < 0.01	-0.9	P < 0.01	-0.79	P < 0.01	-0.88
Plant Height *vs 1-Ci/Ca*	P < 0.01	-0.79	P < 0.01	-0.77	P < 0.01	0.8
Plant height *vs A*	P > 0.05	-0.56	P < 0.01	0.74	P < 0.05	-0.6
Stem diameter *vs Ci*	P < 0.01	0.85	P < 0.01	0.86	P < 0.05	0.65
Stem diameter *vs Ci/Ca*	P < 0.01	0.85	P < 0.01	0.86	P < 0.05	0.65
Stem diameter *vs gs*	P < 0.01	-0.92	P < 0.01	0.88	P < 0.05	-0.7
Stem diameter *vs 1-Ci/Ca*	P < 0.01	-0.85	P < 0.01	-0.86	P < 0.05	-0.65
gs vs Ci	P < 0.01	-0.97	P < 0.01	0.99	P < 0.01	-0.98
gs vs Ci/Ca	P < 0.01	-0.97	P < 0.01	-0.99	P < 0.01	-0.87
gs vs 1-Ci/Ca	P < 0.01	0.97	P < 0.01	0.99	P < 0.01	0.98
Ci vs Ci/Ca	P < 0.01	1	P < 0.01	1	P < 0.01	1
Ci vs 1-Ci/Ca	P < 0.01	-1	P < 0.01	-1	P < 0.01	-1

Photosynthetic rate (*A*), Stomatal conductance (*gs*), Intercellular CO_2 concentration (*Ci*), Ratio of intercellular and atmospheric CO_2 concentration (*Ci/Ca*), Stomatal limitation (1-*Ci/Ca*).

5.5 Discussion

Understanding the physiological mechanism that plays an essential role in plant photosynthesis, growth, and yield is crucial in selecting suitable cultural practices. The present study evaluated different stem training methods on leaf gas exchange of indeterminate tomato produced in dome shape tunnels to identify the most promising stem training methods in improving yield. The observed results showed higher *A* with a single and double stem training method than the two plant per pot training method. This variation is hypothesized to be linked to the competition in water and nutrients 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 resulting to reduce photosynthetic rate (Peterson et al., 1991). Presented results also showed high *gs* with single and double stem compare to two plants per pot.

Stomatal conductance which is responsible for the regulation of stomatal opening also acts as an indicator of water status within the plant. The increase in the rate of *gs* implies high proportions of pores open for entering CO_2. On the other hand, a decrease in *gs* implies low proportions of stomatal pores CO_2 entering (Shezi et al., 2019). Therefore, having high *gs* in single and double would mean a high rate of water absorption by the plant roots. The present study showed a positive correlation in *A* and *gs* of the single and double stem. This finding further confirms that higher *gs* implies a high rate of CO_2 entering the leaf, thus increasing the rate of photosynthesis. Variation in *A* was observed during the time of sampling. The *A* increased in all treatment after transplanting then declined in week 10. This sudden change in *A* during week 10 can be associated with a change of season from summer to autumn.

The observed results also showed non-significant differences from *Ci*, and *Ci/Ca* on different stem training methods despite the increase of *gs* in single stem and double stem. *Ci* determined the amount of CO_2 available in the intracellular space of the leaf. When the stomata open, it automatically increases *gs* resulting in an increase of *Ci* concentration required for the assimilation of carbohydrates (Shezi et al., 2019). In the current study, *Ci* was not dependent on *gs* since there was no significant difference among treatments on *Ci*. The correlation coefficient also showed a strong negative correlation between *Ci*, *Ci/Ca* and *gs*. These findings further confirm that there is no dependence between *Ci* and *Ci/Ca* to stomatal conductance. Similarly, Mashilo et al. (2017) reported that *Ci* was increased irrespective of the decrease in *gs* of bottle gourd under drought stress. The observed result showed significant differences among the time of evaluation on *Ci* and *Ci/Ca*. These parameters were increased from transplant and showed a slight decrease in week 12 until the end of the evaluation, which was a hypothesis to be impacted by the fall of the sun.

The current study found no significant difference among stem training methods on *T*. Transpiration is a loss of water vapour through the stomata. The higher *gs* implies more stomatal pores were open, thus increasing water loss during transpiration (Shezi et al., 2019). Water use efficiency (*WUE*), the ratio of water used by the plant during metabolism to water loss by the plant through transpiration is another factor that plays a huge role in photosynthetic efficiency in plants particularly C3 plants. The current study found no significant difference with regard to *WUE* suggesting that the tested plants had no variation among different trellising methods.

The current study also showed significant differences among growth and yield parameters in response to different stem training methods. The observed results showed an increase in plant height and stem diameter with a single stem than double and two plants per pot stem methods. Similarly, Ara et al. (2007) found that a single stem training method increased plant height than two plants per pot stem methods on tomato cultivar of BARI hybrid. This increase in a single stem is attributed to the less competition of light intensity as well as water and nutrients uptake by the plant which play a critical role in plant growth. The observed results also exhibited a higher number of fruit with double and two plants per pot stem training compared to a single stem. These results were in agreement with Maboko et al. (2011) on tomato cultivar of FA593 where the authors found that double and two plants per pot stem training methods had a higher number of fruit compared to the single stem training method.

The increase in the number of stems growing in a plant also increases the number of fruit on a plant. Therefore, double and two plants per pot stem training produced a high number of fruit per plant because of having two leader stems. On the other hand, a single stem method had high 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 fruit. The study also found high fruit mass with a single stem method than double and two plants per pot stem training methods. Similar results where the single stem had higher fruit mass than two plants per pot in FA593 (Maboko et al., 2011) and BARI tomato cultivar (Ara et al., 2007). The increase and decrease in fruit mass correlate with a balance between the sink and source strength. In a source-limited situation, carbohydrate content in the plants might be low as plants have sufficient sinks to utilize the produced assimilates (Li et al., 2015).

Further, the study showed significant differences among quality parameters which suggested varying responses of plants among the tested stem training methods. The Colour index of two plants per pot and double stem training was higher compared to a single stem. These findings indicate that fruit harvested from two plants per pot and double stem training were more ripen than a single stem. Early ripening in two plants per pot and the double stem was hypothesized to be linked to exposure of the fruit to high light intensity since plants produced with this method had lower vegetative growth. Observed results also showed a high colour index from harvest 1 and 2 and a decline in harvest 3 in all treatments. The decline in harvest 3 was hypothesized to be a result of an increased number of fruit. High fruit load increases the sink strength resulting to competition of assimilates.

The results further exhibited high *TSS* among double and two plants per pot stem training compared to single stem training. *TSS* is the sum of sugars, acids and other minor components in the tomato fruits (Balibrea et al., 2006). *TSS* determined by dry matter content and inversely proportional to fruit size. Beckles (2012) reported that tomato fruit of big size has low *TSS* while small fruit on the other hand, has high *TSS*. This report was in agreement with the present study where double and two plants per pot stem training had smaller fruit accompanied with high *TSS* as compared to single stem. Observed results also showed that *TSS* showed similar trend with colour index during the time of evaluation. This means *TSS* was also dependent on fruit ripening.

TA determined the estimation of acids available in the fruit. *TA* in tomato fruit decrease as the fruit maturity increase (Anthon et al., 2011). This report was 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 *TA*. Two plants per pot and double stem training had a high *TA* than a single stem. The decrease of *TA* in a single stem was linked to the fruit size, bigger fruit has high water content resulting in reduction of sugars with in the fruit. *BrimA* measures the balance between acidity (sourness) and Brix (sweetness) (Jordan et al., 2001; McDonald et al., 2013). The study by Jordan et al. (2001) reported that the flavor of the fruit was more closely related to *BrimA* than *SSC/TA*, and varied with fruit type. Therefore, this index is considered as a superior indicator of 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 higher *BrimA*. Therefore, the results mean the tomato produce with these methods are sweeter than a single stem training method.

5.6 Conclusion

The current study showed that stem training influences plant growth, yield and physiological performances of tomatoes grown in a dome-shape tunnel. Single stem and double stem training methods showed a high photosynthetic rate compared two plants per pot method. As expected, double stem and two plants per pot had a high number of fruit than single stems, respectively. On the other hand, fruit mass of double stem and two plants per pot were respectively lower compared to a single stem which makes them less susceptible to fruit cracking. Therefore, the presented results had revealed that double stem and two plants per pot training methods can be the best method for farmers who seek to optimize their yield and maximize profit. However there is a need for more research focuses on stem training among different cultivars.

5.7 References

Amundson, S, Deyton, D.E., Kopsell, D.A., Hitch, W., Moore, A. & Sams, C.E. 2012. Optimizing plant density and production systems to maximize yield of greenhouse-grown 'Trust'Tomatoes. Horticultural Technology, 22**,** 44-48.

Anthon, G.E., LeStrange, M. & Barrett, D.M. 2011. Changes in pH, acids, sugars and other quality parameters during extended vine holding of ripe processing tomatoes. Journal of the Science of Food and Agriculture, 91**,** 1175-1181.

Ara, N., Bashar, M., Begum, S. & Kakon, S. 2007. Effect of spacing and stem pruning on the growth and yield of tomato. International Journal of Sustainable Crop Production, 2**,** 35-39.

Balibrea, M.E., Martínez-Andújar, C., Cuartero, J., Bolarín, 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. Functional Plant Biology, 33**,** 279-288.

Beckles, D.M. 2012. Factors affecting the postharvest soluble solids and sugar content of tomato (*Solanum lycopersicum L.*) fruit. Postharvest Biology and Technology, 63**,** 129-140.

Dong, C., Shao, L., Wang, M., Liu, G., Liu, H., Xie, B., Li, B., Fu, Y. & Liu, H. 2016. Wheat carbon dioxide responses in space simulations conducted at the Chinese Lunar Palace-1. Agronomy Journal, 108**,** 32-38.

Guan, H.P. & Janes, H.W. 1991. Light regulation of sink metabolism in tomato fruit II. Carbohydrate metabolizing enzymes. Plant Physiology, 96, 922-927.

Hobson, G.E., Adams, P. & Dixon, T.J. 1983. Assessing the colour of tomato fruit during ripening. Journal of the Science of Food and Agriculture, 34, 286-292.

Jordan, R.B., Seelye, R.J & McGlone, V.A. 2001. A sensory-based alternative to brix/acid ratio. Food technology (Chicago), 55, 36-44.

Li, T., Heuvelink, E. & Marcelis, L.F. 2015. Quantifying the source–sink balance and carbohydrate content in three tomato cultivars. Frontiers in Plant Science, 6, 416.

López Camelo, A.F. & Gómez, P.A. 2004. Comparison of color indexes for tomato ripening. Horticultura Brasileira, 22, 534-537.

Maboko, M. & Du Plooy, C.P. 2009. Effect of stem and fruit pruning on yield and quality of hydroponically grown tomato. African Crop Science Conference Proceedings, 9, 27-29.

Maboko, M., Du Plooy, C.P. & Chiloane, S. 2011. Effect of plant population, fruit and stem pruning on yield and quality of hydroponically grown tomato. African Journal of Agricultural Research, 6, 5144-5148.

Maboko, M. & Plooy, C.P. 2008. Effect of pruning on yield and quality of hydroponically grown cherry tomato (*Lycopersicon esculentum*). South African Journal of Plant and 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 physiology and biochemistry, 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 biology and technology, 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*). Journal of Food Engineering, 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 Biology and Technology, 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. Journal of Experimental Botany, 42**,** 1241-1249.

Shezi, S., Magwaza, L.S, Mashilo, J., Tesfay, S.Z & Mditshwa, A. 2019. Photosynthetic efficiency and relationship to mesocarp dry matter content of 'Carmen'avocado (*Persea americana Mill.*) fruit in a cool subtropical climate. Scientia Horticulturae, 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. Scientia Horticulturae, 117**,** 197-202.

Snyder, R. 2007. Greenhouse tomato. Handbook. Mississippi State Ext. p.1828.

CHAPTER 6: CONCLUSIONS AND RECOMMENDATIONS FOR FURTHER RESEARCH

6.1 Introduction

Producing tomatoes under protected cultivation combined with hydroponic system has become an important and commonly used horticultural practice, due to its ability to simulate a natural environment for the plant to grow (Du Plooy et al., 2012). Protected cultivation provide a control for climatic conditions and reduce susceptibility of the crop to pest and diseases. On the other hand, hydroponic system controls the flow of water and nutrients through enhanced water holding capacity, aeration in the root media and plant nutrients supply. Although these types of cultivation system regarded as efficient at improving growth and yield of tomatoes, growing indeterminate cultivars deemed to be challenging particularly for domed shaped tunnels. The physical barrier offered by these structures require regular training of plant growth through trellising and plant population/density control. Stem training and trellising are among the common practices used in horticulture to increase yield and quality of tomatoes produced in tunnels. However, there are so many cases reported, where farmers used this method and fail to reach optimum yield.

This research studied the overall effect of stem training and trellising on growth and yield performance of indeterminate tomato cultivars grown under dome shape tunnel. The main aspects that studied through this research were the efficacy of different type of stem training and trellising method on photosynthetic efficiency of the crop, growth and yield performance as well as nutritional quality of tomato fruits grown under the system

6.2 The effect of different trellising method on photosynthetic efficiency of fertigated indeterminate tomatoes

In chapter 3, an experiment was conducted to assess the effect of different trellising (vertical, early layering and late layering) method on leaf gaseous exchange and chlorophyll fluorescence of tomatoes grown under dome shaped tunnel. The results exhibited variation on the tested trellising methods among, photosynthetic efficiency, growth, yield and quality parameters of tomato produce in dome shape tunnels. Early and late layering showed an increase in photosynthetic rate, transpiration, effective quantum efficiency of photosystem II photochemistry and electron transportation rate compare to vertical trellising. The result indicated that early and late layering accumulated more photosynthetic than vertical trellising. Presented results showed non-significant different in stomatal conductance among trellising methods. The decrease in photosynthetic rate of vertical trellising was not related to stomatal limitation since stomatal conductance was not variable among trellising methods in turn which may mean that other parameters may have played a role in photosynthetic rate differences. Vertical trellising method, at the later stage of growth becomes close to the roof plastic and exposed to high light intensity and high temperature. Therefore, heat stress inhibits photosynthesis through the reduction of ribulose-1,5-bisphosphate (RuBP) supply caused by low ATP synthesis (Tezara et al., 1999). Similar results were found by Hassan (2006) in drought and heat stress of *Triticum aestivum* where photosynthetic rate was significantly reduced. Vertical trellising showed lower electron transportation rate and higher proportion of open reaction centers, meaning that photosynthetic activity was reduced. The results also showed a high electron transportation rate and lower proportion of open reaction centers in late layering and vertical trellising than early layering from transplant until week 12 where early layering and late layering showed an increase with a slight similar trend. These findings further confirm that vertical trellising at a late stage of growth get expose to high heat, thus, resulting to photosynthesis inhibition.

6.3 The effect of different trellising method on growth and yield of indeterminate tomato grown in dome shape tunnels

Chapter 4 evaluated the effect of different trellising method on growth, yield and quality parameters of indeterminate tomato produce in dome shape tunnels. Observed results showed that early layering and late layering had high plant height than vertical trellising method. The reduction in plant height for vertical trellising method might be affected by the burning of epical meristem at the maximum level of the tunnel. Tomato plants growing in high temperature loose integrity of the membranes, thus, resulting to permanent witling (Camejo et al., 2005). Current study exhibited variability with respect to number of fruits and fruit mass among different trellising methods. In contrast, early layering and late layering had higher number of fruits and fruit mass. These findings reveal that the increase in yield of the plant was positive correlated with photosynthetic rate as early and late layering had high photosynthetic rate as corroborated in chapter 3. Further, current study showed non-significant different among quality parameters which suggested no variation among trellising methods. Significant different was observed during the sampling time. Fruits harvested in the in the 2nd harvest had higher Colour index, *TSS, BrimA* and *TSS/TA* than 1st and 3rd harvest, while *TA* on the other hand was reduced in 2nd harvest. These findings evidence that as the fruit mature it reduces *TA*. Similarly Anthon et al. (2011) reported on different tomato cultivars. *TSS* is inversely proportional to the size of fruit (Beckles, 2012). This was in agreement with the present study where the TSS was increasing and decreasing with the fruit mass during the harvest.

6.4 The effect of stem training on growth, yield and physiological responses of indeterminate tomato cultivar grown under dome shape tunnel

In chapter 5, the study investigated the effects of different stem training on growth, yield and physiological responses of indeterminate tomato grown in dome shape tunnels. The current study exhibited higher photosynthetic rate and stomatal conductance with single and double stem training compare to two plants per pot stem. The decrease of photosynthetic rate and stomatal conductance in vertical trellising was linked to plant competition for water and nutrients. Two plants per pot method formed a root ball at a later stage of growth, thus resulting to poor aeration within the roots. Poor aeration inhibit the formation of adventitious roots that promote water uptake with in the plant resulting to reduce photosynthetic rate. The study also showed no variation among tested stem training methods with intercellular CO_2 concentration and ratio of intercellular and atmospheric CO_2 concentration despite the increase of stomatal conductance in single stem and double stem. When the stomata opens, it automatically increase stomatal conductance resulting in the increase of internal CO_2 concentration required for assimilation of carbohydrates (Shezi et al., 2019). However, present study found contrary findings where intercellular CO_2 concentration was not depended in stomatal conductance. Correlation coefficient also showed strong negative correlation between intercellular CO_2 concentration, ratio of intercellular and atmospheric CO_2 concentration compared to stomatal conductance, which further confirm non-dependence of this parameters to stomatal conductance. Similarly, Mashilo et al. (2017) reported that intercellular CO_2 concentration was increased irrespective of decrease in stomatal conductance of bottle gourd under drought stress.

The current study also showed significant differences among growth and yield parameters in response to different stem training methods. The observed results showed high plant height and stem diameter with single stem than double and two plants per pot stem method. However, double stem and two plants per pot stem training exhibited higher number of fruits compare to single stem. These results were in agreement with Maboko et al. (2011) on tomato cultivar of FA593. Single stem method had high vegetative growth, which is associated with the promotion of flower abortion because of poor air circulation with in the plant leaf canopy, thus reducing the number of fruits formed. On the other hand, single stem exhibited high fruit mass than double and two plants per pot stem training method. Similar result where single stem had higher fruit mass than two plant per pot in FA593 (Maboko et al., 2011) and BARI tomato cultivar (Ara et al., 2007). Single stem has low marketable fruits and very susceptible to fruits cracking (Maboko and Du Plooy, 2009). Large fruit size in single stem training method was hypothesis as the main cause of fruit cracking, thus, resulting to reduce of marketable fruits. The present study also showed significant differences among quality parameters, which indicated varying responses of plants among the tested stem training methods. Observed results showed high colour index with two plants per pot and double stem training compare to single stem. These findings indicated that fruits produced in two plants per pot and double stem training were more ripen than single stem. Early ripening in two plants per pot and double stem was hypothesize to be link to exposure of the fruits to high light intensity since plants produced with this method had lower vegetative growth. On the other hand, the current study showed higher *TSS*, *TA* and *BrimA* with two plants per pot and double stem training had high

TA than single stem. *TSS* is the sum of sugars, acids and other minor components in the tomato fruits (Balibrea et al., 2006). Beckles (2012) reported that tomato fruit of big size has low *TSS* while small fruits on the other hand, has high *TSS*. This report was in agreement with the present study where double and two plants per pot stem training had smaller fruits accompanied with high *TSS* as compared to single stem. The decrease of *TSS*, *TA* and *BrimA* in single stem was link to the fruit size; bigger fruit has high water content resulting to reduction of sugars with in the fruit.

6.5 Conclusion

The present study showed a significant contribution in identifying the trellising method and stem training method has a positive influence on improving plant physiology, growth and yield of tomato produced in dome shape tunnels. The research found that early and late layering trellising increase photosynthetic rate, growth and yield than vertical trellising method. On the other hand, vertical trellising has been reported with a problem of height limitation and burning of epical meristem in dome shape tunnel. Therefore, the presented results have given some indications that early and late layering trellising methods can be the best methods that can be used by resource-constrained farmers in dome shape tunnel to improve physiological efficiency, growth and yield. The research further found that double stem and two plants per pot stem training improve photosynthetic efficiency, yield and quality of indeterminate tomato produce in dome shape tunnel compare to single stem training.

6.6 Recommendations for further research

The following recommendations may be made, based on observations made during the study

- To do more research on different trellising methods in different cultivars.
- Investigate the response of different trellising method during winter months.
- Combine trellising methods with different stem training to analyse the physiological response and yield of indeterminate tomato grown in dome shape tunnels.

6.7 References

Anthon, G.E., LeStrange, M. & Barrett, D.M. 2011. Changes in pH, acids, sugars and other quality parameters during extended vine holding of ripe processing tomatoes. Journal of the Science of Food and Agriculture, 91**,** 1175-1181.

Ara, N., Bashar, M., Begum, S. & Kakon, S. 2007. Effect of spacing and stem pruning on the growth and yield of tomato. International Journal of Sustainable Crop Production, 2**,** 35-39.

Balibrea, M.E., Martínez-Andújar, C., Cuartero, J., Bolarín, 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. Functional Plant Biology, 33**,** 279-288.

Beckles, D.M. 2012. Factors affecting the postharvest soluble solids and sugar content of tomato (*Solanum lycopersicum L.*) fruit. Postharvest Biology and Technology, 63**,** 129-140.

Camejo, D., Rodríguez, P., Morales, M.A., Dell'Amico, J.M., Torrecillas, A. & Alarcón, J.J. 2005. High temperature effects on photosynthetic activity of two tomato cultivars with different heat susceptibility. Journal of plant physiology, 162**,** 281-289.

Du Plooy, C.P., Maboko, M., Van den Heever, E. & Chiloane, S. 2012. Research and technology transfer by the Agricultural Research Council to sustain the South African hydroponic industry. Acta horticulturae, 947**,** 147-152.

Hassan, I. 2006. Effects of water stress and high temperature on gas exchange and chlorophyll fluorescence in Triticum aestivum L. Photosynthetica, 44**,** 312-315.

Maboko, M. & Du Plooy, C.P. 2009 Effect of stem and fruit pruning on yield and quality of hydroponically grown tomato. African Crop Science Conference Proceedings, 9, 27-29.

Maboko, M, Du Plooy, C.P. & Chiloane, S. 2011. Effect of plant population, fruit and stem pruning on yield and quality of hydroponically grown tomato. African Journal of Agricultural Research, 6**,** 5144-5148.

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 physiology and biochemistry, 120**,** 75-87.

Shezi, S., Magwaza, L.S, Mashilo, J., Tesfay, S.Z. & Mditshwa, A. 2019. Photosynthetic efficiency and relationship to mesocarp dry matter content of 'Carmen'avocado (*Persea americana Mill*.) fruit in a cool subtropical climate. Scientia Horticulturae, 253**,** 209-216.

Tezara, W., Mitchell, V., Driscoll, S. & Lawlor, D. 1999. Water stress inhibits plant photosynthesis by decreasing coupling factor and ATP. Nature, 401**,** 914.