EVALUATION OF THE PHYSIO-MORPHOLOGICAL CHARACTERISTICS AND PRODUCTIVITY OF TOMATO CULTIVARS IN THE TROPICS USING THE LOW-NODE PINCHING ORDER AT HIGH-DENSITY CULTIVATION IN RECIRCULATING HYDROPONIC CONDITIONS

January 2022

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Graduate School of Horticulture

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（千葉大学審査学位論文）

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Content

Chapter 1. General Introduction

1-1. Importance of Tomato

Tomato (*Solanum lycopersicum* L.) ranks among the most consumed vegetables globally (Nasir et al., 2015). The product is consumed fresh, cooked, or in a processed form (Ahmed et al., 2012). Tomato fruit provides 60 mg and 40 mg of daily body needs for adults and children, respectively (Leoni and Jongen, 2002). Tomato fruit contains a high amount of lycopene, which reduces the risk of some diseases in humans (Arab and Steck, 2000; Freeman and Reimers, 2010).

Tomato serves as a source of income since it is the only employment opportunity for most farmers and stakeholders in Africa. Due to the job creation opportunity, Anang et al. (2013) reported that tomato is an avenue for poverty alleviation in Ghana.

1-2. Current Production Challenges

Production of tomato in the tropics like Ghana is season-dependent. Most of the farmers cultivate in the open field and run out of business in the dry season. The processing industry is adversely affected in this regard. Also, lack of high technology irrigation equipment has been reported to affect tomato cultivation in the same region (Adenuga et al., 2013). The yield of tomato in Ghana, as published in FAOSTAT (2018), was 7.6 t ha^{-1}. Meanwhile, the demand for the product increases daily, and the volume produced cannot even meet local market demand alone.

1-3. Future Challenge (Climate Change)

Climate change has been predicted to cause a 5-10% yield loss in tomato (Abdelmageed and

Gruda, 2009; Booker et al., 2009; Guodaar, 2015). Emphatically, the reduction in the yield is due to reduced plant biomass and fruit set (Li et al., 2012; Oshima et al., 1975). Heat stress emerging from climate change could result in blossom end rot, uneven ripening (Rosales et al., 2010), inhibits lycopene synthesis (Gruda and Tanny, 2014), and reduce ascorbate content in tomato (Wang and Frei, 2011). Proper management of the climate in the less-advanced greenhouses is very challenging (Fink et al., 2009). In general, it has been predicted by Silva et al. (2017) that the growth and yield of tomato plants will be adversely affected by heat and drought stress in the nearest future. Also, it has been predicted that damage to crop plants by phytopathogen and insect pests will be devastating (Johkan et al., 2011). To ensure sustainable vegetable crop production in the face of climate change, De la Peña and Hughes (2007), Bita and Gerats (2013), Solh and Ginkel (2014) suggested the use of heat-tolerant tomato cultivars with high water use efficiency.

1-4. Mitigating Against Tomato Production Challenges

It is anticipated that protected cultivation will increase the yield of tomato. The greenhouse has been recommended by Singh and Asrey (2005). They stated that tomato produced in the greenhouse is high in yield and quality. Fortunately, a tropical-oriented greenhouse (Envirodome) was introduced into Ghana in 2014 to enhance vegetable crop production. However, the yield of tomato has not significantly improved since the introduction of the Envirodome. The performance of vegetable crops may not solely lie in the use of the greenhouse. But then, an appropriate cultivation system may also be an excellent tool for enhancing vegetable crop productivity under greenhouse conditions. Tomato production in the Envirodome has been practiced in the soil and poor substrate culture conditions. Compared to Japan, achieving a high yield importantly requires the state-of-the-art technology in terms of cultivation system (hydroponics).

1-5. The Low-Node Pinching Order at High-Density Planting System

The low-node pinching order at high-density planting (LN&HD) is a short-term (70-120 days) cultivation system with a harvest made from 1-4 trusses. This system is noted as a widely used technique for increased yield and year-round production of tomato (Watanabe, 2006). The LN&HD is easy to automate (Okano et al., 2001). With the LN&HD, the grower can select the appropriate cultivar according to the prevailing climatic condition instead of the Dutch system. It had been challenging to produce tomato in Japan during summer due to the severity of high temperatures. However, Johkan et al. (2013) reported that year-round production of tomato is made possible using the LN&HD. The LN&HD system could minimize high summer (tropical) temperature damage on tomato than the Dutch system (Giacomelli et al., 1994). Additionally, labour and skills required for this cultivation system are low compared to the Dutch system, which is more laborious. Furthermore, the structural arrangement of the Envirodome (greenhouse) especially, the trellising height, is relatively too short to permit the adoption of the Dutch system in Ghana.

The greenhouse space is often limited in size; therefore, cultivating crops in such confinement should duly be optimized. The optimum yield of tomato may be achieved at optimum plant density. According to Maboko et al. (2011), the total yield and fruit quality are influenced by plant density and the number of trusses. Plant density affects the yield of tomato, while decapitation or pinching shortens the growth period, reducing the cost of inputs (Okano et al., 2001).

Improving the yield of tomato cultivars grown in the tropics like Ghana has been a long yearning of all growers. However, state-of-the-art technology (cultivation system) for improving yield and fruit quality is not readily available. Additionally, climate change is advancing very fast, and by reports, it will become a significant threat to tomato production in the tropics. These issues, therefore, call for immediate interventions.

1-6. Objectives of this work

1-6-1. Main objective

Enhance sustainable tomato production by increasing the yield of tomato cultivars in the tropics using an efficient, affordable, and adoptable cultivation system.

1-6-2. Specific objectives

a. Select high-yielding tomato cultivars in the tropics for year-round production.
b. Test the performance of a heat-tolerant tomato cultivar against high-temperature stress conditions.
c. Evaluate resource use efficiencies for tomatoes grown in hydroponic conditions.
d. Manipulate rootzone restrictions to increase the yield of tomatoes in the tropics.

Chapter 2. Effect of Spacing and Topping on The Performance of Hydroponically Grown Tomato under Tropical Conditions

2-1. Introduction

Tomato (*Solanum lycopersicum* L.) has been known as one of the most important crops consumed worldwide. It is consumed in diverse dishes in various places. Growing tomato in the tropical region all year round on a sustainable basis is a paramount desire. Tropical areas like Ghana are still striving with an abysmal yield of 20 t ha^{-1} y^{-1} compared to the Netherlands, which, according to FAOSTAT (2018), produces 558.9 t ha^{-1} y^{-1}. In the dry seasons, the demand for tomato supersedes its supply, and therefore prices become exorbitantly high. In such circumstances, there is sole reliance on importing tomato, which further increases the price. Growing tomato under tropical conditions is faced with lots of challenges such as; high temperature, drought, flood, pests, diseases, poor production techniques, and lack of technical skills.

With the advent of the greenhouse facility, most of the current challenges are controlled to some extent. However, greenhouse control of extremely high temperatures in the tropics, as indicated by Mutwiwa et al. (2007), is very difficult. Tropical climates are known for high day and night temperatures, especially during dry seasons. Air temperatures are usually high, and this often affects the reproductive phases of tomato. Sato et al. (2000) report that high air temperature significantly results in a low percent fruit set. Also, Suzuki (2006) added that high temperatures, especially during summer, inhibit fruit production of tomato. To address this challenge, proven cultivation techniques under greenhouse conditions have to be adopted.

Ghana, a tropical country, is characterized by more than 90% of consumers of tomato, which lay more emphasis on quantity. This, therefore, implies that production techniques that could enhance a higher yield of tomato sustainably in the greenhouse should be adopted. In adverse climatic conditions, Watanabe (2006) reported that the low node-order pinching at a high-density planting system (LN & HD) had become a practical and widely used technique for year-round production for increased yields. Under hydroponics techniques, the LN & HD cultivation system is a useful tool for achieving a high tomato yield (Endo et al., 2007; Kiriiwa, 2008). Similarly, Giacomelli et al. (1994) indicated that temperature damage to tomato growth in the summer under the high wire cultivation system could be controlled by adopting the single truss tomato system at high plant density.

Plant spacing is one management practice that greatly influences tomato performance, especially under hot temperature conditions (Abdel-Mawgoud et al., 2007). Janes and McAvoy (1989) stated that tomato yield could be increased should the single truss production with a high-density cultivation system be adopted. They further indicated that with this production system, the cultivation period is reduced, low labour is required, yields are consistent, and it could be automated. Tamai (2014) indicated that the crop could be cultivated 3.5 times per year, especially when LN&HD is adopted. According to (Kozai, 2005), this production system is better than the traditional production system, which is more labour intensive, long production period, variable in yields, and plants suffer high summer temperature effects. Several researchers have recommended a single to three trusses at a high-density planting. Higashide and Heuvelink (2009) reported 36 kg m^{-2} $year^{-1}$ for tomato yield in Japan using the single-truss production system at a plant density of 10 plants m^{-2}. In a similar matter, Zhang et al. (2015) reported a high tomato yield of 1.74 kg for plants pinched at the third truss. Reports from several research findings recommend the single truss system with a high-density planting. Inevitably, plants grown at a very high density will encounter a shade effect, which may negatively influence the photosynthetic capacity. In such a situation, Lu et al. (2012) have recommended using supplemental lighting, which adds more to the total cost of production.

However, it is economically essential to reconsider that prices of seeds meant for greenhouse production are very high and, therefore, the need to obtain optimum productivity from such seeds on cultivation. Additionally, there is a need to eliminate artificial supplemental lighting because it is not affordable in the tropics. Adequate plant density could be adopted to eliminate the need for supplemental lighting. Because of this, the work sought to evaluate the optimum (truss number with optimum plant-density for optimum yield under tropical conditions. In the tropics like Ghana, tomato production using the LN&HD has not been reported in the literature. It is positively anticipated that the said cultivation system would increase tomato yield under hot tropical conditions. This study aimed to select high-yielding tomato cultivars subjected to the low node pinching order at a high-density cultivation system under high summer temperature conditions.

2-2. Materials and Methods

2-2-1. Plant materials

Tomato cultivars used in the study were Jaguar, Lebombo, and Lindo. Jaguar and Lindo were obtained from Technisem, Savanna seed limited company, while Lebombo was obtained from Proseed Company. Characteristics of the cultivars used in the study are described in Table 2-1.

Table 2-1. Characteristics of tomato cultivars used in the study

Cultivar	Growth habit	Maturity	Average fruit weight	Shoulders	High Resistance
Jaguar	Indeterminate	65 -70 days	100 -130 g	uniform	F, St, and V
Lebombo	Indeterminate		80 -100 g		BW
Lindo	Indeterminate	65-70 days	80- 100 g	uniform	TMV, F, St, and V

F=*Fusarium oxysporum*; BW=bacterial wilt; TMV= tobacco mosaic virus; St=*Stemphylium* sp; V=Verticillium wilt

2-2-2. Site and Nursery

The study was conducted in the greenhouse at the Kashiwanoha campus of Chiba University, Japan, between May 23, 2018, and September20, 2018, to coincide with the summer. The seeds were sown in cell trays using cocopeat as the sowing medium on May 23, 2018. The germinated seeds were kept in an artificial growth chamber with a light intensity of 280 µmol m^{-2} s^{-1} for 16 hours; 1000 µmol mol^{-1} CO_2; day/night temperatures maintained at 23/18ºC, and nutrient solution at EC 0.12 S m^{-1} was supplied as sub-irrigation once, daily.

2-2-3. The Hydroponic System

The system consisted of 20 m long cultivation benches (Figure 2-1). On each bench was planting troughs laid with a white impervious cloth. The impermeable material with the trough served as a gutter through which the unabsorbed nutrient solution flowed from the upper slope of the bench into the return tank (reservoir). Planting panels with 10 cm spaced cells were mounted on top of the troughs. A 0.5 L volume capacity planting pots were 90% filled with cocopeat. The bases of the planting pots were lined with a water-permeable net lining. The net linings allowed for a capillary movement of the nutrient solution to the plants and, at the same time, filtered the substrate from getting into the nutrient solution. The nutrient solution was formulated according to half the strength of the Enshi standard formula (Hori, 1966): 0.7 mM NH_4-N, 8 mM NO_3-N, 1.3 mM PO_4-P, 4 mM K, 2 mM Ca, 1 mM Mg, 2 mM SO_4-S, 3 ppm Fe, 0.5 ppm B, 0.5 ppm Mn, 0.02 ppm Cu, 0.05 ppm Zn, 0.01 ppm Mo. The plants were automatically irrigated by the nutrient film technique (sub-irrigation). Sensors automatically regulated the electrical conductivity (EC) and pH of the nutrient solution at 5.5-6.5 and 0.12 S m^{-1}, respectively. Seedlings were carefully transplanted into the 0.5 L pot filled with cocopeat. Transplants were trellised using a twine with clips.

Figure 2-1. Tomato grown at high density in NFT (nutrient film technique)

2-2-4. Transplanting and Treatments

Transplanting of seedlings was carried out 21 days after germination. Plant spacing of 0.2 and 0.3m (4.2 and 2.8 plants m^{-2}, respectively) was adopted. Plants were pinched (topped) on the seventh and ninth week after transplanting (WAT) when flowers in the second and the fourth truss, respectively, were fully set. Flowers upon full opening were sprayed with 1.0 mL L^{-1} of 4-chlorophenoxyacetic acid to enhance fruit set. The 3x2x2 factorial in Randomized Complete Block Design in three replications was adopted as the experimental design.

2-2-5. Morphometrics

The morphometric parameters taken were height, girth, leaf number, and SPAD value at the second, fourth, and thirteenth week after transplanting (WAT). Also, days to 50% flowering and fruiting were determined. Plant height and girth were measured using a ruler and vernier calipers, respectively. Plant girth was initially measured at the first two true leaves and subsequently at the leaf below the first and the last trusses. Chlorophyll content was measured with a chlorophyll meter, SPAD-502 (Konica-Minolta Inc., Tokyo, Japan).

2-2-6. Dry Matter Partitioning

The distribution of dry matter was determined by measuring: leaf area; plant, shoot, root and fruit dry matters (DM); root-shoot ratio, and percent dry matter partitioned to fruits at the thirteenth WAT. The leaf area was determined using a photo camera to scan the detached leaves. The scanned leaves were subjected to the Lia25 (https://www.agr.nagoya-u.ac.jp/~shinkan/LIA32/author-e.html) software to calculate the leaf area. DM of leaves, stem, root, and the fruits were determined through oven drying at 72°C for ten days after samples showed constant dry weights.

2-2-7. Yield and Yield Components

This component comprises fruit number, percent fruit set, percent blossom end rot (BER) affected fruit, marketable yield per plant, yield per area. Percent fruit set was determined as a fraction of the total number of fruits to the total number of flowers. On the other hand, BER was determined as a fraction of affected fruits to the total number of fruits.

2-2-8. Fruit Quality

Components of fruit quality measured were total soluble solids (TSS), titratable acidity (TA), and TSS/TA ratio. The TSS with the TA was measured using a K-BA100R spectrophotometer (Kubota, Yao, Japan) to scan the fruits. TSS/TA ratio was determined as a fraction of TSS to TA.

2-2-9. Data Analysis

Data obtained were analyzed using the Analysis of Variance GenStat (Rothamsted Research, Harpenden, UK) while Tukey's honestly significant difference was used to separate the means at $p<0.05$.

2-2-10. Greenhouse Ambient Temperature and Humidity During the Cropping Cycle

The daily maximum and the minimum readings for temperature and humidity were recorded using the Smart Sensor AR 867 thermo-hygrometer, Arco Science and Technology, China.

2-3. Results

2-3-1. Greenhouse Ambient Temperature and Humidity During the Cropping Cycle

The readings are shown in Figures 2-2 and 2-3.

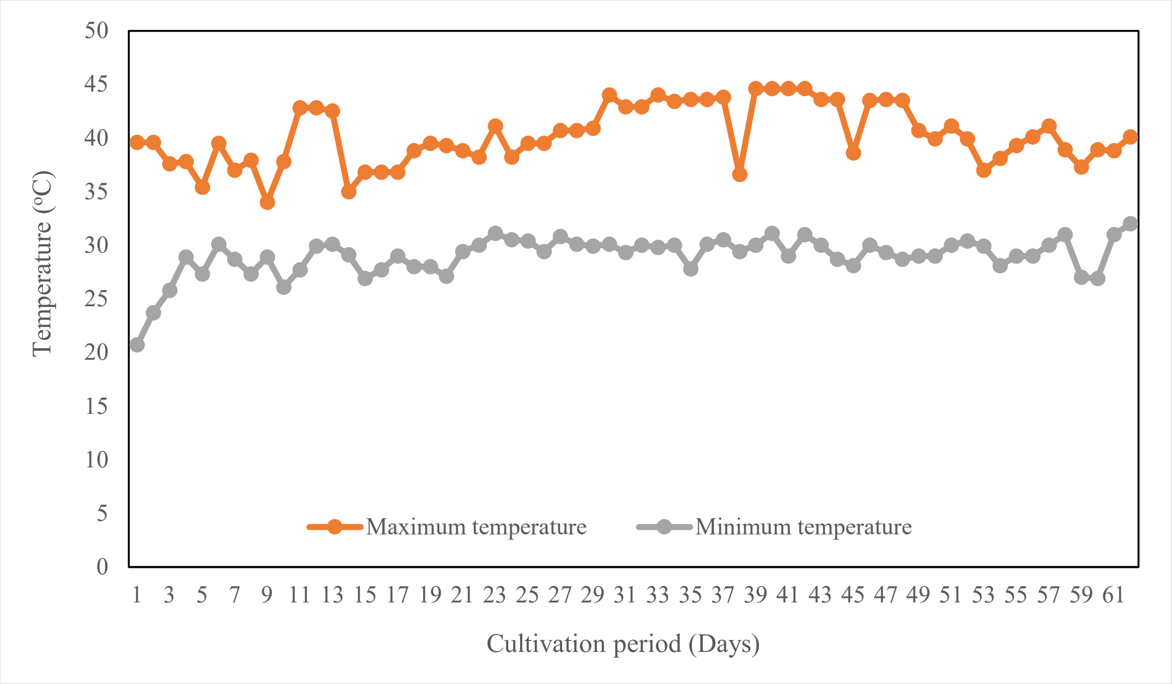

Figure 2-2. Greenhouse ambient temperature recorded during cultivation

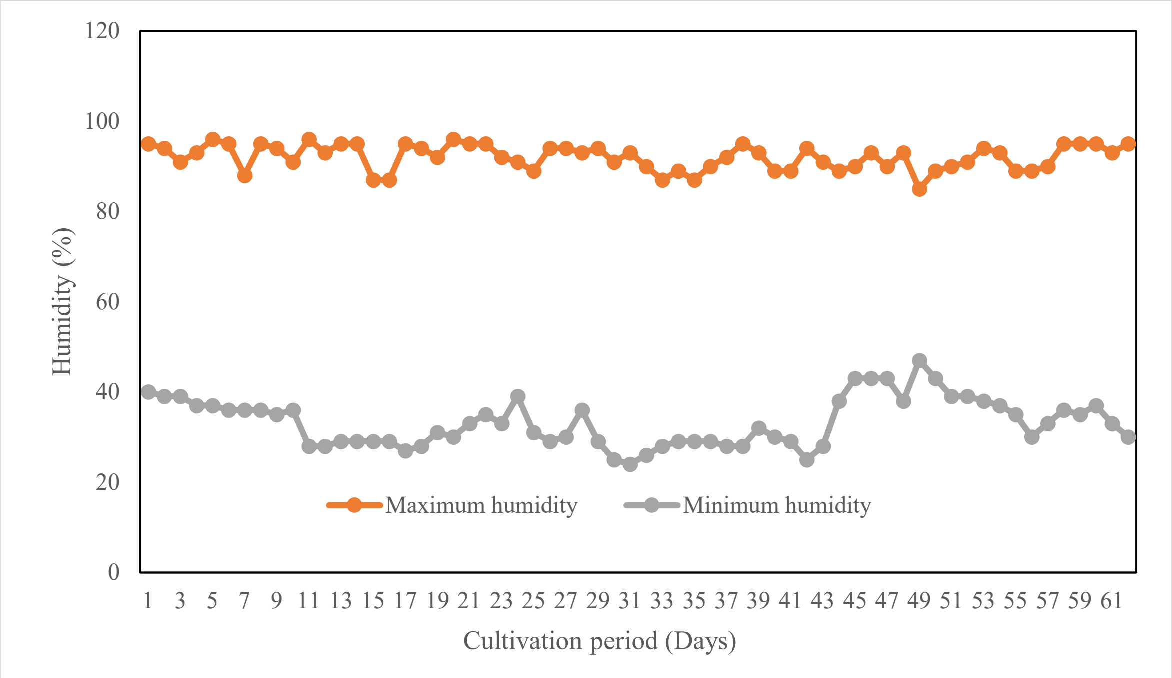

Figure 2-3. Greenhouse ambient humidity recorded during cultivation

2-3-2. Morphometrics

From Table 2-2, results showed that cultivar and spacing did not influence plant height significantly ($p<0.05$) at the second and the fourth weeks after transplanting (WAT). However, at the thirteenth WAT, the result indicates that Lebombo significantly grew taller (141.8 cm) than Jaguar (116.3 cm) and Lindo (117.1 cm). Plants pinched at the fourth truss were significantly 30.9 cm taller than those pinched at the second truss. Cultivar x spacing interaction had no significant influence on plant height at the thirteenth WAT. Cultivars pinched at different truss numbers varied significantly in plant height at the thirteenth WAT. The tallest plants of 162.4 cm were recorded in Lebombo pinched at the fourth truss while the shortest. 92.6cm was recorded in Jaguar pinched at the second truss. No significant interaction effect was recorded for cultivar, spacing, and pinching at the thirteenth WAT.

Plant girth was not affected by cultivar and spacing at the second WAT. At the fourth and the thirteenth WAT, Jaguar recorded a significant ($p<0.05$) thinner stem diameter than the other two cultivars (Table 2-2). On the other hand, spacing and pinching did not influence stem diameter throughout the growing period. No significant interaction effects were observed. Results from Table 2-3 showed that cultivar, spacing, and cultivar x spacing interaction did not significantly affect the leaf number of the tomato cultivars throughout the growing period.

Table 2-3 indicates that Jaguar recorded significantly ($p<0.05$) the highest chlorophyll content at the second and the fourth WAT than the other cultivars. A similar trend was observed at the thirteenth WAT; however, Jaguar and Lindo recorded did not differ significantly. At the thirteenth WAT, plants grown at 30 cm apart recorded 3.1 more SPAD value than those spaced at 20 cm. Lebombo spaced at 20 cm recorded the lowest chlorophyll content (52.6) compared to other treatments, although not significantly different from some treatments. Cultivars topped at different truss numbers recorded similar chlorophyll content at the thirteenth WAT.

Table 2-2 showed that Jaguar and Lebombo respectively set flowers in 2 and 3 days earlier than Lindo. In a similar trend, the two cultivars set fruits in 9 and 3 days, respectively, earlier than Lindo.

Table 2-2. Effect of spacing and topping on plant height, girth, and days to fruit set of tomato cultivars

	Height (cm)			Girth (mm)				
Treatment	2 WAT	4 WAT	13 WAT	2 WAT	4 WAT	13 WAT	Df	Dfr
Cultivar (C)								
Jaguar	54.4a	111.4a	116.3a	8.7a	10.1a	11.2a	36.0a	41.5a
Lebombo	55.4a	115.3a	141.8b	8.9a	11.2b	12.9b	35.8a	47.3b
Lindo	51.1a	108.8a	117.1a	9.5a	11.2b	12.5b	38.9b	50.9c
Spacing (S)								
20 cm	55.3	112.4	122.3	8.9	10.81	12.03	36.9	46.4
30 cm	51.9	111.3	119.2	9.1	10.85	12.39	36.9	46.7
$HSD_{(0.05)}$	3.8	4.4	4.3	0.57	0.186	0.851	0.593	0.652
Truss number (T)								
2			105.3			12.44		
4			136.2			11.97		
$HSD_{(0.05)}$			4.33			0.650		
Interactions								
C x S	NS	NS	NS	NS	**	NS	NS	NS
C x T			**			NS		
S x T			**			NS		
C x S x T			NS			NS		

NS = no significance; ** = significant difference; WAT = weeks after transplanting; Df and Dfr= days to 50% flowering and fruit set; Same letters in same column are not significantly different at ($p<0.05$) according to Tukey's HSD.

Table 2-3. Effect of spacing and topping on leaf number and SPAD value of tomato cultivars

Treatment	Leaf number			SPAD value		
Cultivar (C)	2 WAT	4 WAT	13 WAT	2 WAT	4 WAT	13 WAT
Jaguar	10.4a	15.6a	15.6a	43.4b	56.3b	59.4b
Lebombo	10.6a	16.7a	16.7a	36.3a	52.3a	55.2a
Lindo	10.9a	15.8a	15.8a	38.3a	52.7a	57.5ab
Spacing (S)						
20 cm	10.7	16.2	16.2	39.3	53.8	55.8
30 cm	10.6	16.9	16.9	39.4	53.7	58.9
$HSD_{(0.05)}$	0.39	0.9	0.93	2.7	1.7	2.7
Truss number (T)						
2						57.7
4						57.1
$HSD_{(0.05)}$						1.9
Interactions						
C x S	NS	NS	NS	NS	NS	**
C x T			NS			**
S x T			NS			NS
C x S x T			NS			NS

NS = no significance; ** = significant difference; WAT= weeks after transplanting; Same letters in same column are not significantly different at ($p<0.05$) according to Tukey's HSD.

2-3-3. Yield Components

Results from Table 2-4 show that Jaguar and Lebombo respectively recorded a fruit set of 94.9% and 97.6% significantly ($p<0.05$) higher than Lindo, which recorded 88.7%. Plant spacing did not significantly influence the fruit set. Plants topped at the second truss recorded 97.9% fruit set, which was significantly higher than those topped at the fourth truss, which recorded 89.5%. Lindo topped at the fourth truss recorded 81.5% fruit set as the lowest compared to other treatments.

Results from Table 2-4 indicated that Lebombo significantly produced 14.4 fruits per plant, which was twice that of Jaguar and five fruits more than Lindo. Spacing had no significant influence on fruit number. The topping of plants at the second truss significantly produced 4 four fruits less than those topped at the fourth truss. Fruit number per plant was significantly ($p<0.05$) influenced by cultivar, plant density, and topping interactions. Lebombo plants topped at the fourth truss produced the highest fruit number of 16.2 and 17.8 at a spacing of 20 cm and 30 cm, respectively. The smallest fruit number of 5.5 and 5.7 were recorded in Jaguar plants topped at the second truss with spacings of 30 cm and 20 cm, respectively.

Table 2-4 showed that Jaguar significantly produced 0.68 kg as the highest yield, followed by 0.483 kg per plant for Lebombo. Lindo produced the lowest yield of 0.375 kg per plant. Spacing did not significantly influence yield per plant. The topping of plants had no significant effect on marketable yield. There was no interaction effect on yield per plant.

The highest yield, 2.4 kg m^{-2}, was recorded in Jaguar and followed by 1.7 kg m^{-2} for Lebombo. Lindo, on the other hand, produced the lowest yield of 1.3 kg m^{-2}. Plants spaced at 20 cm produced 2.2 kg m^{-2}, which was significantly higher than 1.4 kg m^{-2} for plants spaced at 30 cm. Topping of plants did not markedly affect yield per area. Yield per area was significantly affected by cultivar, plant density, and truss number interactions. Jaguar at high plant density and topped at the fourth truss produced 3.1 kg m^{-2} as the highest yield per area. The lowest (0.86 kg m^{-2}) was recorded in Lindo grown at low density and topped at the second truss.

In Jaguar and Lindo, their marketable yields were reduced by 44.1 and 47.1%, respectively, due to blossom end rot (BER). Lebombo, on the other hand, recorded less than 1% of BER incidence. Spacing did not significantly influence the occurrence of BER. Plants topped at the second truss suffered 6% BER more than those topped at the fourth truss. Topping Jaguar at the second truss reduced its yield by 51.7% by BER. However, no occurrence of BER was observed in Lebombo topped at the second node.

2-3-4. Fruit Quality

According to Table 2-4, cultivar and plant density showed no significant effect on total soluble solids TSS. Plants topped at the fourth truss recorded 0.2% significantly higher Brix than plants topped at the second truss. No significant interaction effect was observed on TSS. Cultivar and spacing showed no significant effects on titratable acidity. Plants pinched at the fourth truss produced higher (0.3 g $g^{-1)}$ titratable acidity (TA) than those pinched at the second truss. Lebombo spaced at 0.2 m recorded the highest TA (0.6 g g^{-1}), while the least (0.5 g g^{-1}) was recorded in the same cultivar spaced at 0.3 m. No other significant interaction influenced the TA. The cultivar, spacing, and topping had no significant effects on TSS/TA ratio. Similarly, no significant interaction effect on TSS/TA ratio was observed. The Jaguar, Lindo, and Lebombo fruits in high temperature stress conditions are shown in Figure 2-4.

Table 2-4. Effect of spacing and topping on yield, blossom end rot, and fruit quality of tomato cultivars

Treatment	Percent fruit set	Fruit number $plant^{-1}$	Fruit weight $plant^{-1}$ (kg $plant^{-1}$)	Yield $area^{-1}$ (kg m^{-2})	BER (%)	TSS (brix%)	TA (g g^{-1})	TSS/TA ratio
Cultivar (C)								
Jaguar	94.9b	7.6a	0.68c	4.74c	44.1b	6.8a	0.51a	13.5a
Lebombo	97.6b	14.4b	0.48b	3.32b	0.2a	6.7a	0.50a	13.6a
Lindo	88.7a	9.1a	0.38a	2.64a	47.1b	6.9a	0.51a	14.0a
Spacing (S)								
20 cm	93.9	10.3	0.53	4.43	29.8	6.9	0.52	13.5
30 cm	93.6	10.4	0.49	2.71	31.1	6.7	0.49	13.9
HSD$_{(0.05)}$	5.03	2.8	0.11	0.42	3.80	0.25	0.033	0.901
Truss number (T)								
2	97.9	8.4	0.47	3.26	33.6	6.7	0.49	13.8
4	89.5	12.3	0.56	3.87	27.3	6.9	0.52	13.6
HSD$_{(0.05)}$	4.015	2.3	0.10	0.76	3.8	0.23	0.029	0.91
Interactions								
C x S	NS	**	NS	**	NS	NS	**	NS
C x T	**	NS	NS	NS	**	NS	NS	NS
S x T	NS	NS	NS	NS	NS	NS	NS	NS
C x S x T	NS	**	NS	**	NS	NS	NS	NS

NS = no significance; ** = significant difference; WAT = weeks after transplanting; Same letters in same column are not significantly different at ($p<0.05$) according to Tukey’s HSD; BER= blossom end rot; TSS=total soluble solids; TA= titratable acidity.

Figure 2-4. (a) Jaguar, (b) Lindo and (c) Lebombo fruits in high temperature stress conditions

2-3-5. Dry Matter Partitioning

According to Table 2-5, Lebombo recorded significantly ($p<0.05$) the highest leaf area of 17.2 dm^{2,} followed by 12.8 dm^{2} for Jaguar. Lindo recorded 11.2 dm^{2} as the lowest leaf area at the thirteenth WAT. Spacing did not significantly influence the leaf area. Plants topped at the fourth truss recorded a 3.7 dm^{2} leaf area significantly more than those topped at the second truss. In terms of interactions, only spacing and truss number significantly affected leaf area. Plants pinched at the fourth truss with 0.2 or 0.3 m spacing recorded 14.7 and 16.4 dm^{2,} respectively. These were markedly higher than the leaf area recorded in the plants subjected to other treatments.

Lebombo significantly produced 13 g DM more than the other cultivars. Spacing did not affect plant DM significantly. Plant DM was 16.9 g higher in plants pinched at the fourth truss than those pinched at the second truss. Plant DM was significantly affected by cultivar and spacing interaction. Lebombo planted at 0.3 m spacing recorded the highest plant DM (127.0 g) though not significantly higher than some treatments. Lindo planted at 0.3 m spacing recorded the lowest plant DM of 104.2 g. Cultivar and node pinching interaction significantly affected plant dry matter production. Pinching Lebombo at the fourth truss recorded significantly higher plant DM (139.5 g) relative to other treatments. No other interactions effects were observed on plant DM.

Dry matter partitioned to shoot at the thirteenth WAT significantly differed in cultivars. Lebombo partitioned more DM to shoot than the other cultivars. Plant spacing did not significantly influence dry matter partitioning to the shoot. Plants pinched at the fourth truss significantly produced 6.44 g more shoot DM than those pinched at the second truss. No significant interaction effect was observed for dry matter production to shoot.

Dry matter partitioning to root among cultivars differed significantly. Lindo partitioned 5.1 and 3.7 g more DM to roots than Jaguar and Lebombo, respectively. Plant spacing had no significant influence on dry matter distribution to the roots. Pinching of plants did not affect the root DM significantly. There was no significant interactions effect on DM partitioned to root.

Lindo and Jaguar recorded a root/shoot ratio of 0.17 and 0.12, significantly higher than that of Lebombo. Plant spacing and node pinching showed no significant effect on the root/shoot ratio. No significant interaction effect was observed on the root/shoot ratio. Dry matter partitioned to fruit was significantly influenced in cultivars. More than 50% of the DM was partitioned in the fruits of Jaguar. The other two cultivars partitioned more DM towards vegetative growth.

Dry matter allocated to fruits was not significantly influenced by spacing. High node pinched plants (four trusses) significantly partitioned 12.6 g more DM in fruits than those that received low node pinching. Cultivar and spacing interaction influenced fruit DM partitioning significantly. Jaguar spaced at 20 cm partitioned the highest DM of 61.7 g (54.22% of total plant DM) to fruit. Dry matter allocated to fruit was significantly influenced by cultivar and pinching interaction. The plants pinched at the fourth truss partitioned more DM to fruit than those pinched at the second truss.

Table 2-5. Effect of spacing and topping on dry matter partitioning of tomato cultivars at 13 WAT

		Dry matter (g)					
Treatment	Leaf area (dm^2)	Total plant	Shoot	Root	Fruit	Root-shoot ratio	FDM (%)
Cultivar (C)							
Jaguar	12.8b	112a	36.3a	15.5a	60.2b	0.43b	53.7b
Lebombo	17.2c	125b	54.6c	16.9a	53.5ab	0.31a	42.3a
Lindo	11.2a	112.1a	44.3b	20.5b	47.2a	0.47b	41.7a
Spacing (S)							
20cm	13.3	118.8	44.5	18.1	56.2	0.42	47.3
30cm	14.2	113.9	45.7	17.1	51.1	0.39	44.5
$HSD_{(0.05)}$	2.52	9.82	6.20	2.37	8.38	0.073	5.31
Truss number (T)							
2	11.9	107.9	41.9	18.7	47.4	0.46	43.8
4	15.6	124.8	48.3	16.5	60	0.35	47.9
$HSD_{(0.05)}$	2.17	7.93	5.77	2.27	7.28	0.063	5.19
Interactions							
Cultivar x spacing	NS	**	NS	NS	**	NS	**
Cultivar x truss	NS	**	NS	NS	**	NS	NS
Spacing x truss	**	NS	NS	NS	NS	NS	NS
C x S x T	NS	NS	NS	NS	NS	NS	NS

FDM= Percent dry matter allocated to fruits; WAT= weeks after planting

2-4. Discussions

2-4-1. Morphometrics

A higher internode length characterized the Lebombo cultivar, and that might have made the cultivar grow taller than the other cultivars (data not shown). Higher truss number in cultivars might have induced much taller plants than those with the lower truss number. Higher chlorophyll content in Jaguar might be due to cultivar genetic differences. Plants that were grown in a low density recorded a higher chlorophyll content. The result might be attributed to a higher interception of light because such plants had wider spacing than plants grown in a high density.

2-4-2. Yield Components

The higher fruit set recorded in Jaguar and Lebombo indicates that both cultivars possess good attributes of heat tolerance. Plants with the higher truss number recorded a lower fruit set due to an adverse effect of extreme summer temperatures, as stressed by Sato et al. (2000). However, the lower fruit number recorded in the plants topped at the second truss was due to blossom end rot (BER). Marketable yield (weight of total harvested fruits) of 1.73 kg plant^{-1} was reported for plants topped at the third truss (Zhang et al., 2015). The yield obtained in this study was comparatively lower. The reduced yield was attributed to the high incidence of BER, which accounted for the high yield loss.

Besides, the plant density adopted in this study was much lower than that reported in the previous study. Closer spacing (high-density planting) of plants produced a higher yield per unit area. The yield of the Jaguar cultivar recorded (being the highest among the cultivars) was 3.8 times lower than the yield reported by Higashide and Heuvelink (2009). The vast difference in the yield may be due to cultivar genetic diversity, the difference in plant density adopted, and the yield loss to BER. Plants of Jaguar and Lindo were highly susceptible to BER compared to Lebombo, which showed a high level of resistance. Lebombo might have probably possessed a stronger xylem network at the blossom end than the other cultivars. This has been suggested by Ho et al. (1993) that tomato genotypes possessing a stronger xylem network are less susceptible to BER. Yield loss of almost 50% in the two susceptible cultivars confirmed a report by Taylor et al. (2004) that BER may reduce marketable tomato yield up to about 50%. Plants topped at the second truss recorded BER more than those topped at the fourth truss. This might probably be because the first fruit emergence coincided with the incidence of high summer temperatures. This incidence agrees with Watanabe (2006), which reported that tomato subjected to high temperatures results in blossom end rot.

2-4-3. Dry Matter Partitioning

The higher leaf area recorded in Lebombo might be due to differences in genetic attributes among the cultivars. The higher number of leaves in plants pinched at the fourth truss might have accounted for the higher leaf area than the plants pinched at the second truss. Irrespective of spacing, a higher truss number produced more leaves hence the higher leaf area. Lebombo plants were better producers of photosynthates relative to the other cultivars. Due to a higher photosynthetic area, Lebombo topped at the fourth truss were better producers of DM compared to the different cultivars. Lebombo cultivar partitioned more of its photosynthates towards vegetative growth, while Jaguar recorded more partitioning towards reproductive growth. Plants pinched at the fourth truss were higher in shoot biomass and produced more shoot DM than those pinched at the second truss. There was more investment of photosynthates in root at the expense of fruit in Lindo compared to other cultivars. This might have accounted for the low yield in the same cultivar. The Jaguar cultivar exhibited a higher sink strength compared to the other cultivars. Dry matter distribution in Jaguar was more geared towards yield, and this might have accounted for the higher yield compared to the other cultivars. Due to the more photosynthetic area available to plants topped at the fourth truss, more photosynthates were partitioned into the fruit. However, percent DM partitioned to fruit for the plants topped at the second, and the fourth trusses were similar.

Chapter 3. Effect of Plant Density on The Yield of Hydroponically Grown Heat-Tolerant Tomato under Summer Temperature Conditions

3-1. Introduction

Increasing the yield of tomato to meet market demand sustainably is a major challenge facing Ghana. The challenge emanates from the fact that tomato production in Ghana has been based on inadequate cultivation systems, lack of high-yielding cultivars, and others. Additionally, tomato crop cultivation under extremely high temperatures, especially in the tropics, is besetting with a low or poor fruit set. The poor fruit set results in a reduced yield of tomato, especially in the dry seasons.

Furthermore, climate change issues like high temperatures are advancing with threats to tomato crop cultivation in the tropics (Sawicka et al., 2017; Wang et al. 2017) and other regions (Souri and Hatamian, 2019). It has been reported by Johkan et al. (2011) that, aside from the adverse physiological impacts, high temperature could also favour the proliferation of insect pests and diseases. These negatively affect tomato production. In general, it has been predicted by Gunawardena and De Silva (2016) that the growth and yield of tomato plants will be adversely affected by high temperatures. The yield of tomato is expected to reduce by 5-10% (Abdelmageed and Gruda, 2009; Booker et al., 2009; Guodaar, 2015). Too high temperatures reduce fruit set (Li et al., 2012) and induce blossom end rot (Rosales et al., 2010).

In advancing climate change, it has been reported that heat-tolerant tomato cultivars are better to cultivate (Johkan et al., 2011; Kugblenu et al., 2013). Such cultivars have been reported to set fruit, even under high night temperatures above 21ºC (Abdalla and Verkerk, 1968) maintain net photosynthetic rate, under heat stress (Zhou et al., 2015).

For proper utilization of the cultivation area, optimum plant density is required (Ara et al., 2007). Heuvelink et al. (2009) showed that crop yield could be affected by excessively low or high plant density. They indicated that plant density could induce competition and shade effect.

According to Menberu et al. (2012), a decrease in plant density increases the unmarketable yield of tomato. It was reported that a high plant density increased marketable fruit yield (Law-Ogbomo and Egharevba, 2009). Conversely, Geremew et al. (2010) reported that plant density does not significantly affect the total fruit yield of tomato. It was further emphasized by Akintoye et al. (2009) that yield of tomato per unit area increased with an increase in plant density. Fruit number increases with an increase in plant density.

In 2014, greenhouse technology was introduced for tomato and other vegetable crop cultivation in Ghana. However, it had not been without difficulty managing temperatures inside the greenhouse. Fink et al. (2009) stressed that proper management of the climate in the less advanced greenhouses is very challenging. Also, appropriate tomato cultivars have not been cultivated in tune with the changing climate. Consequently, the performance of tomato has been adversely affected because of a low fruit set and high incidence of blossom end rot. In tropical regions with high temperatures, De la Peña and Hughes (2007), Bita and Gerats (2013), and Solh and van Ginkel (2014) suggested using heat-tolerant tomato cultivars for high fruit set.

This study sought to increase the yield of a heat-tolerant tomato in a high-density planting under high summer temperature conditions (like Ghana's). This work was to be performed in a state-of-the-art hydroponics system, which is not available in Ghana. This system is characterized using a low substrate volume (reducing production cost) with a recirculating technique (conserving water and nutrients). With the conservation of resources, a reduced production cost could render the cultivation system affordable and adoptable. The outcome of this work was intended for adoption and practice in Ghana.

3-2. Materials and Methods

3-2-1. Plant Materials and Treatments

The study was conducted in the summer period, between May 23 and August 20, 2018, in the greenhouse of Chiba University, Japan.

Three cultivars of tomato were evaluated at a plant density of 2.7 and 4.1 plants per unit area. A heat-tolerant tomato 'Nkansah HT' (obtained from University of Ghana, Forest and Horticultural Crops Research Center, Kade-Ghana) was evaluated along with two tropical cultivars. The tropical cultivars were Jaguar and Lebombo (obtained from Technisem, Savanna Seed Company limited, Longue-Jumelles, France, and Proseed company, Benoni-South Africa, respectively. Information regarding heat tolerance for the Jaguar and the Lebombo cultivars has not been provided in the literature.

The experiment was laid out in a 3 x 2 factorial in the randomized complete block design with three replications. Each treatment consisted of twenty plants, and data were analyzed by the analysis of variance using the GenStat (Rothamsted Research, Harpenden, UK) while Tukey's honest significant difference ($LSD_{0.05}$) was used to separate the means at $p<0.05$.

3-2-2. Growing Conditions

The seeds were sown in coconut shell fiber (Cocopeat, Top Co. Ltd, Japan) on May 23, 2018. The germinated seedlings were transferred to an artificial lighting chamber equipped with a day/night temperature of 23/18 °C, CO_2 supply at 1000 μmoL moL^{-1} for a 16 h photoperiod. These conditions were adopted in order to raise stout and healthy seedlings. The nutrient solution was supplied according to half-strength of the Enshi formula (Hori, 1966), described below. A specially designed 0.5 L capacity planting pot, with a water-permeable bottom, was filled with coconut shell fiber as the substrate. Transplanting was carried out on the third week after germination into a recirculating nutrient film. Uptake of nutrients and water was by capillary action. The half-strength Enshi formula adopted was; 0.7 mM NH_4-N, 8 mM NO_3-N, 1.3 mM PO_4-P, 4 mM K, 2 mM Ca, 1 mM Mg, 2 mM SO_4-S, 3 ppm Fe, 0.5 ppm B, 0.5 ppm Mn, 0.02 ppm Cu, 0.05 ppm Zn, 0.01 ppm Mo. The electrical conductivity of the nutrient solution was maintained at 0.12 S m^{-1} and the pH 5.5-6.5 throughout the cropping cycle. The heat-tolerant cultivar had stopped flowering at the fourth week after transplanting. In order to synchronize the growth of the three cultivars, plants of the Lebombo and the Jaguar were topped at the third leaf above the second truss.

3-2-3. Plant Growth

Plant height, leaf number, and chlorophyll content were measured on the twelfth weeks after transplanting (WAT). The plant height was determined using a ruler from the base to the uppermost part of the plant. The chlorophyll content was measured at the leaves below the youngest trusses, using a chlorophyll meter, SPAD-502 (Konica-Minolta Inc., Tokyo, Japan). Three plants were randomly sampled, where the leaves were detached and scanned with a camera. The scanned leaves were analyzed for the leaf area using (https://www.agr.nagoya-u.ac.jp/~shinkan/LIA32/, accessed on August 21, 2019). The leaf area ratio (LAR) was calculated as the leaf area divided by the total plant dry mass. The leaf weight ratio (LWR) was determined as the total leaf dry weight divided by the total plant dry weight.

3-2-4. Dry Matter Production and Partitioning

At the twelfth week after transplanting, three randomly sampled plants were separated into leaves, stem, root, and fruit. The different components were oven-dried at 72 °C until a constant dry weight was obtained on the sixth day. Summing up all the components, the mean total plant DM was determined. The shoot's DM was determined as the sum of the leaf and the dry stem weights.

3-2-5. Reproductive Growth

Days to fifty percent anthesis was determined as the number of days within which fifty percent of the plants flowered. Fruit set percent was determined as the total number of fruits formed, divided by the total number of flowers present per plant. Blossom end rot (BER) percent was calculated as the total number of fruits affected by the incidence of BER divided by the total number of fruits produced per plant. The yield per unit area was calculated as the fresh fruit weight per plant multiplied by 2.7 or 4.1 plants per meter, respectively. Fruits were selected from the various treatments and scanned for the total soluble solids (TSS) using the K-BA100R spectrophotometer (Kubota, Yao, Japan).

3-2-6. Greenhouse Ambient Temperature and Humidity During the Cropping Cycle

The daily maximum and the minimum readings for temperature and humidity were recorded using the Smart Sensor AR 867 thermo-hygrometer, Arco Science and Technology, China. The readings are shown in Figures 2-2 and 2-3.

3-3. Results

3-3-1. Plant Growth

The plants cultivated at a high density grew taller than those at low density by the twelfth week after transplanting (Table 3-1). The Nkansah heat-tolerant (HT) recorded the lowest plant height compared to Lebombo and Jaguar. Significantly, the Lebombo plants cultivated at a high density were taller than the plants in the other treatments.

Plant density did not significantly influence the number of leaves produced. Leaf number produced in the HT was 24 to 26 higher than Lebombo and Jaguar. The HT produced a higher leaf number than the other cultivars in all the treatments.

High density planting showed a reduced chlorophyll content than the low-density planting. The Jaguar plants showed a higher chlorophyll content than the plants in the other cultivars. Chlorophyll content was not affected by plant density in the HT cultivar. However, the other cultivars showed a reduced chlorophyll content in a high plant density.

Leaf area was not affected by plant density (Table 3-1). The Lebombo produced a higher leaf area than the other cultivars.

Plant density did not affect the photosynthetic area for the individual cultivars.

Plant density did not alter the leaf area ratio significantly. Compared to the other cultivars, the HT plants recorded the lowest leaf area ratio. The leaf area ratio recorded in the individual cultivars did not differ with plant density.

Leaf weight ratio was not influenced by plant density (Table 3-1). The leaf weight ratio observed in the HT was similar to the Jaguar but was significantly lower than the Lebombo. The leaf weight ratio recorded in the different cultivars did not vary with plant density.

Table 3-1. Effect of plant density on growth of tomato cultivars at 12 WAT

Cultivar (C)	Height (cm)	Leaf number	SPAD value	Leaf Area (cm^2)	LAR (cm^2 g^{-1})	LWR (mg g^{-1})
HT	78.2c	36.3a	46.8b	1270b	6.8c	161.2b
Lebombo	121.1a	12.3b	48.5b	1430a	12.9a	226.2a
Jaguar	92.6b	10.4c	55.6a	1131c	10.6b	158.2b
HSD$_{(0.05)}$	8.2	1.3	2.9	129.4	1.3	30
Plant density (PD)						
High	102.4a	19.7a	48b	1248a	10.5a	180.5a
Low	92.2b	19.6a	52.6a	1307a	9.8a	183.2a
HSD$_{(0.05)}$	6.6	1.1	2.3	105.6	1.1	20
C x PD						
HT x high	82.8de	36.3a	45.8d	1258bc	6.8d	167.5b
HT x low	73.6e	36.3a	47.7cd	1283bc	6.9d	154.9b
Lebombo x high	128.3a	12.5b	45.8d	1514a	13.6a	220.2a
Lebombo x low	113.8b	12.2b	51.2bc	1346ab	12.4ab	232.3a
Jaguar x high	96c	10.1c	52.4b	1148c	11.0bc	153.8b
Jaguar x low	89.2cd	10.6bc	58.8a	1114c	10.3c	162.6b
HSD$_{(0.05)}$	11.5	1.8	4.1	182.9	1.8	40

HT =Nkansah heat-tolerant tomato; LAR=leaf area ratio: LWR=leaf weight ratio.
Figures with the same letter in the same column are not significantly different according to Tukey's HSD at $p<0.05$

3-3-2. Dry Matter Production and Partitioning

The HT plants produced the highest plant dry matter (DM) compared to the other cultivars (Table 3-2). Plant DM production did not vary with plant density. The individual cultivar showed no variation in plant DM production with plant density. Dry matter allocated to shoot, root, and fruit did not differ with plant density. Shoot, root, and fruit, DM were higher in the HT than the other cultivars. Partitioning of DM in the individual cultivars showed no variation with plant density.

Table 3-2. Effect of plant density on dry matter partitioning in tomato cultivars at 12 WAT

Cultivar (C)	TPDM (g plant^{-1})	SDM (g)	RDM (g)	FDM (g)
HT	186.7a	78.2a	19.7a	88.8a
Lebombo	106.5b	50.3b	16.4b	42.7c
Jaguar	110.4b	32.8c	17.4b	57.4b
HSD$_{(0.05)}$	9.9	5.7	2.4	7.7
Plant density (PD)				
High	134.1a	53.7a	18.1a	62.3a
Low	134.9a	53.8a	17.5a	63.6a
HSD$_{(0.05)}$	8.1	4.7	1.9	6.3
C x PD.				
HT x high	186.2a	79.2a	19.6ab	87.4a
HT x low	187.1a	77.1a	19.9a	90.1a
Lebombo x high	111.6b	50.2b	18.7ab	42.7c
Lebombo x low	109.3b	50.5b	16.0b	42.7c
Jaguar x high	104.5b	31.8c	16.0b	56.7b
Jaguar x low	108.4b	33.8c	16.7ab	57.9b
HSD$_{(0.05)}$	14	8.1	3.4	10.9

HT =Nkansah heat-tolerant tomato; TPDM=total plant dry matter; SDM= shoot dry matter; RDM= root dry matter; FDM= dry matter allocated to fruit; Figures with the same letter in the same column are not significantly different according to Tukey's HSD at $p<0.05$

3-3-3. Reproductive Growth and Total Soluble Solids

The cultivars showed a variation in terms of days to fifty percent flowering. The HT flowered 5-6 days earlier than the other cultivars (Table 3-3). Plant density did not affect the number of days to flowering. The HT plants grown in both high and low densities flowered earlier than the other treatments.

Fruit set percent was not markedly affected by plant density, cultivar, or their interactions (Table 3-3).

HT and Lebombo plants showed no incidence of blossom end rot. However, 51% of Jaguar's fruits was affected by blossom end rot. Plant density did not affect the incidence of blossom end rot. Under the low and high plant densities conditions, fruits of the Jaguar cultivar were highly affected by blossom end rot compared to the HT and Lebombo.

The HT plants produced more fruits per unit area than Lebombo and Jaguar (Table 3-3).

Plants that received a high-density planting produced 24 more fruits per unit area than in the low-density planting. The lowest number of fruits was observed in the Jaguar plants that received the low-density planting. HT cultivar grown at high density produced 55 more fruits than same cultivar grown at low density.

The highest marketable yield (weight of total harvested fruits) per unit area was recorded in the HT plants, while the lowest was observed in the Lebombo (Table 3-3). High-density planting produced 0.7 kg more yield than the plants cultivated at a low density. The highest yield per unit area was produced in the HT and Jaguar plants, which were cultivated at high density compared to the other treatments.

Total soluble solids of the fruits did not vary with plant density, cultivar, and the interaction between plant density and cultivar (Table 3-3).

Table 3-3. Effect of plant density on reproductive components and total soluble solids of tomato cultivars

Cultivar (C)	Df (days)	FS (%)	FNa	BER (%)	Yield (kg m^{-2})	TSS (%Brix)
HT	30b	99.5a	150.7a	0.0b	2.7a	6.4a
Lebombo	35.8a	98.3a	40.4b	0.0b	1.4c	6.7a
Jaguar	36a	99.6a	19.6c	51.73a	2.3b	6.7a
$HSD_{(0.05)}$	0.6	1.3	3.8	7.1	0.2	0.4
Plant density (PD)						
High	33.9a	99.4a	82.3a	17.2a	2.5a	6.7a
Low	33.9a	98.9a	58.1b	17.3a	1.8b	6.5a
$HSD_{(0.05)}$	0.5	1.0	3.1	5.8	0.1	0.3
C x PD						
HT x high	30b	99.6a	179.1a	0.0b	3.2a	6.4a
HT x low	30b	99.3a	122.3b	0.0b	2.3b	6.4a
Lebombo x high	35.8a	98.4a	44.1c	0.0b	1.5cd	6.9a
Lebombo x low	35.8a	98.2a	36.7d	0.0b	1.3d	6.4a
Jaguar x high	36a	100a	23.8e	51.5a	2.9a	6.6a
Jaguar x low	36a	99.3a	15.3f	51.9a	1.7c	6.7a
$HSD_{(0.05)}$	0.9	1.8	5.4	10	0.31	0.6

HT =Nkansah heat tolerant tomato; Df= days to fifty percent flowering; FS%= percent fruit set; Fna= fruit number per unit area; BER= percent fruit affected by blossom end rot; TSS= total soluble solids; Figures with the same letter in the same column are not significantly different according to Tukey's HSD at $p<0.05$

The appearance of Nkansah HT grown in NFT under high temperature stress conditions are shown in Figure 3-1.

Figure 3-1. Nkansah HT grown in NFT under high temperature stress conditions

3-4. Discussions

3-4-1. Plant Growth

Cultivars grown at a high density produced taller plants than those at low density. At high plant density, the plants might have competed for more sunlight through stem elongation, which might have increased the plant height more than plants grown at low density. This result confirms the findings of Tuan and Mao (2015) and Gupta and Shukla (1977), that plant height increased with high-density planting. Lebombo cultivar produced taller plants than HT and Jaguar, probably because the internode length for the Lebombo plants was longer than the other cultivars.

The HT plants produced a more significant number of leaves than the other cultivars. The HT cultivar was a determinate type, with three stems from which many leaves were produced. However, Leaf number was not affected by plant density, which is confirmed in Mahmoud's (2005) findings.

High-density planting reduced chlorophyll content by 9.6% because of the shade effect. Plant density did not affect chlorophyll content in the HT compared to the other cultivars. The individual leaves in the HT plants were relatively smaller in size. As a result, the effect of leaf shading might have been minimized compared to the other cultivars.

Larger leaf size was produced in the Lebombo plants. This accounted for the larger leaf area in the Lebombo plants than the other cultivars. During high summer temperature (tropical) conditions, dry matter production efficiency and partitioning in Lebombo leaves were higher than the other cultivars.

3-4-2. Dry Matter Production and Partitioning

There was higher DM in HT cultivar’s shoot, root, and fruits than the other treatments. This accounted for the higher total plant DM produced in the HT compared to the other cultivars. The higher leaf number and stem in the HT plants might have induced a higher sink strength than the Lebombo and Jaguar. Additionally, the larger fruit number produced in the HT might have increased its sink strength compared to the other cultivars. Production of more photosynthates might have been induced in the HT plants because of the higher sink strength.

Lebombo cultivar showed a higher photosynthetic area with higher efficiency in DM production. However, more of the DM produced was allocated to the leaves. The sink strength in the Lebombo fruits might have been limited. Therefore, dry matter assimilation to other organs was reduced compared to the HT. There was a low photosynthetic area but high efficiency in DM production in the Jaguar plants. Dry matter allocation to fruit was higher than in the vegetative parts.

3-4-3. Reproductive Growth and Total Soluble Solids

Anthesis in the HT cultivar occurred six days earlier than the other cultivars. This observation may be due to genetic differences among the three cultivars.

Regardless of the high summer temperatures, the percent fruit set was very high among the three cultivars. This result disagrees with Li et al. (2012) that high temperatures reduce fruit set. The response of tomato fruit set to high temperatures stress is dependent on the cultivar.

However, the Jaguar cultivar showed a higher susceptibility to blossom end rot (BER) in the summer period. Marketable fruit number in the Jaguar was reduced by 51% due to BER. This result is in line with Rosales et al. (2010) that high temperatures induce BER, as the reproductive organs (fruits) are highly hampered (Zinn et al., 2010). However, this result showed that some cultivars are not affected under heat stress regarding susceptibility to BER. Gunawardena and De Silva (2016) indicated that the yield of tomato would adversely be affected during high temperatures. The HT and the Lebombo showed no record of BER compared to the Jaguar. Most probably, the fruits of the HT and the Lebombo cultivars had a higher store of calcium at their blossom ends than the Jaguar. These two cultivars might have also developed a better water and nutrient use efficiency with higher membrane integrity (Momcilovic and Ristic, 2007) than the Jaguar.

A high-density planting increased fruit number by 42% due to more plants present per unit area. This result contradicts the findings of Balemi (2008) that fruit number increased with low plant density. It was argued that there was a low competition for resources for plants grown at low density. The HT produced more fruits per unit area, with a reduced fruit size than Lebombo and Jaguar. On the other hand, the Jaguar recorded the lowest fruit number per unit area. The reduction in fruit number for the Jaguar plants was due to the high incidence of BER. Adams and Ho (1992) have explained this that cultivars which produce large fruit size are more susceptible to blossom end rot.

The yield of tomato per unit area increased by 43% when cultivated at high density. This work's findings showed that plant density affects yield, against Geremew et al. (2010) who reported that plant density does not affect the yield of tomato. The highest yield per unit area was recorded in the HT cultivar. This is because a higher total plant dry matter was produced with a higher dry matter allocation to the HT's reproductive sinks (fruits). The more significant fruit number in the HT might have induced an increased reproductive sink demand for assimilates than the other cultivars.

Similarly, the Jaguar cultivar grown at a high plant density produced a high yield as the HT. With a high dry matter allocated to fruit in the Jaguar, the reproductive sink demand might have increased hence a higher yield than the Lebombo. Cultivar planting at a high density increased the yield per unit area of tomato by 15-70%. This agrees with Ara et al. (2007) and Akintoye et al. (2009) that an increase in plant density increases the yield of tomato per unit area. In this study, the nutrient film hydroponic system might have induced a high osmotic gradient around the root zone, thus increasing the total soluble solids than that reported by Nkansah et al. (2003) in Ghana.

Chapter 4. Evaluation of Tropical Tomato for Growth, Yield, Nutrient and Water Use Efficiency in Recirculating Hydroponic System.

4-1. Introduction

Tomato is highly consumed in Ghana. Ghana's national tomato transporters and traders' association (GNTTTA, 2018) reported that the country is the highest consumer of the product in Africa. It was further indicated that 90% of tomato produced in Burkina Faso (a neighbouring country) is consumed in Ghana. However, the production volume in Ghana remains low, with an annual yield of 8.6 t ha^{-1} (FAOSTAT, 2018). Producing enough to meet both local and international demand sustainably is not feasible without state-of-the-art technology.

In 2014, some greenhouse facilities (tropically customized) were introduced into the country to boost tomato production sustainably. In spite of this, tomato production output has not yet improved significantly compared to Japan and the Netherlands. This is an indication that the appropriate cultivation systems at cost-effective levels have not so far been adopted.

Cultivation of tomato under hydroponics conditions for increased yield and quality has been reported. Work on the low-node order pinching at high plant density (LN&HD) cultivation system has been reported to be effective in enhancing productivity and quality of tomato (Watanabe, 2006). This system has been defined according to Takahashi et al. (2012) as a short cultivation period of 70–120 days, where harvesting is made from 1–4 trusses at high plant-density. This cultivation system has been recommended due to its efficiency in resource utilization. In contrast to soil cultivation, which has been affected by many challenges, this system is efficient in mitigating such challenges. Efficient use of limited resources to achieve optimum output remains the desire of every rational producer (farmer). The use of water, nutrients, space, and labour is highly efficient with this system (Tamai, 2014). A study was conducted earlier (Ayarna et al., 2019) on three tropical tomato cultivars for yield under hydroponic conditions using sub-irrigated pot cultivation. The study adopted the LN&HD

system in recirculating nutrient film techniques (NFT). A yield of 84.9 t ha^{-1} per year was recorded in Jaguar, with just about 50% yield loss to blossom end rot (BER).

Apart from the issue of BER, recirculating sub-irrigation NFT for low substrate culture results in reduced fruit size; hence, yields are consequently compromised. Because of this, it was reported (Dufour and Guérin, 2005) that hydroponics by drip irrigation enhances good yield, higher fertilizer use efficiency decreases production cost, and reduces the risk of environmental pollution. The drip method in recirculating hydroponics could also offer a better insight for determining water and nutrient uptake characteristics for a given cultivar under prevailing climatic conditions. The adequate amount with accurate timing of irrigation could influence the yield and quality of tomato (Sezen et al., 2010).

The LN&HD using recirculating drip hydroponics could be used to improve the yield of tomato. The system will also enhance water and nutrient use efficiencies, as reported by Raviv et al. (2007). Plant roots involved in water and nutrient uptake are usually restricted in this system due to low substrate volume. These restricted roots are known to produce finer young roots (Bar-Tal et al., 1994), which are efficient in the uptake of water and nitrogen (Bar-Tal et al., 1995). A study on the attributes of water and nutrient uptake in tomato plants is of great importance. This is because the cost of fertilizers is high while water becomes somewhat scarce, particularly in the dry seasons. This system will help in the proper use and management of resources at economic levels.

However, studies on most tropical tomato cultivars for growth, yield, water, and nutrient use efficiencies with the LN&HD are not available. In addition, this hydroponic cultivation system has never been reported in Ghana so far as tomato production is concerned. This system was ultimately intended to be established for tomato cultivation in Ghana. The current study sought to evaluate the growth, yield, water and nutrient use efficiencies of tropical-oriented tomato under the LN&HD system using drip recirculating hydroponics in the greenhouse. The system was expected to become the most efficient and economical way of boosting tomato production in the tropics like Ghana.

4-2. Materials and Methods

4-2-1. Cultivation Conditions and Treatments

The study was conducted in the greenhouse at the Kashiwanoha campus of Chiba University, Japan, between 29 August 2018 and 14 January 2019.

Cultivars used in the study were Jaguar and Momotaro York. These cultivars were obtained from Techisem, Savanna Seed Company limited (Longué-Jumelle, France), and Takii Seeds Company Ltd (Kyoto, Japan).

Seeds were sown in cell trays using cocopeat as the sowing medium. The germinated seeds were kept in an artificial growth chamber. The chamber was equipped with a light intensity of 280 μmol m^{-2} s^{-1} for 16 h, 1000 μmol mol^{-1} CO_2, and the day/night temperatures maintained at 23/18 °C. The constitution of the nutrient solution was 0.7 mM NH_4-N, 8 mM NO_3-N, 1.3 mM PO_4-P, 2 mM K, 2 mM Ca, 1 mM Mg, 2 mM SO_4-S, 3 ppm Fe, 0.5 ppm B, 0.5 ppm Mn, 0.02 ppm Cu, 0.05 ppm Zn, and 0.01 ppm Mo. An ebb and flow hydroponic technique was adopted in supplying the nutrient solution to the seedlings once a day.

The hydroponic system was arranged in benches of 15 m long. Each bench had panels that suspended the planting pot sitting on troughs which served as a channel for draining unabsorbed water back to the return tank. Planting pots of 500 mL volume capacity were 90% filled with cocopeat. Spacing adopted was 0.2 by 1.3 m. The electrical conductivity (EC) of the nutrient solution was 0.12 S m^{-1}, while the pH was maintained between 5.5 and 6.5. The nutrient solution was pumped to the root zone of each plant through drips periodically (Figure 4-1).

Transplanting of seedlings was carried out 21 days after germination. Plants were pinched (topped) at 42 and 56 days after transplanting (DAT) respectively for Jaguar and Momotaro after three leaves above the fourth truss were fully developed. The topping was carried out in line with the findings of Logendra et al. (2001).

Flowers upon full opening were sprayed with 1 mL L^{-1} 4-chlorophenoxyacetic acid to enhance fruit set.

Figure 4-1. Tomato cultivation in a recirculating drip hydroponic system

4-2-2. Morphometrics

The morphometric parameters such as height, girth, leaf number, and chlorophyll content (SPAD) were measured fortnightly. Additionally, days to 50% flowering and fruiting were determined. Plant height and girth were measured using a ruler and vernier calipers, respectively. Plant girth was initially measured at the first two true leaves and subsequently at the leaf below the succeeding trusses. Chlorophyll content was measured with SPAD 502 plus (Konica-Minolta Inc., Tokyo, Japan). The chlorophyll content was determined on the leaves below the immediate truss and the leaves below the succeeding trusses.

4-2-3. Water and Nutrient Use Efficiencies

Water uptake for the first harvest (70 DAT) was determined as the initial water supplied less the amount of water left (unabsorbed). This parameter was measured periodically when the nutrient solution volume had drastically reduced, thereby requiring a renewal. Water use efficiency (WUE) was determined as a ratio of fruit weight to total water uptake per plant at first harvest (70 DAT).

Nutrient uptake was determined by collecting samples of the nutrient solution at the end of each period. The samples were analyzed for nutrients using the Dionex ICS1100 ion chromatography (Thermo Fisher Scientific Inc., Waltham, MA, USA). Nutrient use efficiency (NUE) was expressed as a ratio of the fresh fruit weight to the total nitrogen uptake per plant at first harvest.

4-2-4. Physiological Characteristics

Physiological attributes such as photosynthetic rate, leaf conductance, and transpiration were measured using the LI-6400 (LI-COR, Lincoln, NE, USA). Measurement was carried out on the immediate leaf below the second truss between 1:30 and 2:30 p.m.

4-2-5. Growth Parameters

Relative growth rate (RGR) was expressed as the rate of dry mass increase per unit of plant mass over a given time. Net assimilation rate (NAR) was expressed as dry matter increment per unit leaf area per unit of time. All the leaves were detached, and photo scanned using a camera. The scanned photos were analyzed for the leaf area, using the Lia32 (https://www.agr.nagoya-u.ac.jp/~shinkan/LIA32/author-e.html) software.

4-2-6. Dry Matter Partitioning

Distribution of dry matter (DM) was determined by measuring the total plant DM and its partitioning to shoot, root and fruit; and the root-shoot ratio. The DM of leaf, stem, root, and fruit were determined through oven drying at 72 °C for ten days when dry weights of samples became constant. The DM contents were determined fortnightly and used to calculate the growth parameters.

Root tissue density (RTD) is a measure of resource uptake strategies in plants. Plants with lower RTD have more fine roots for the uptake of water and nutrients. RTD influences water and nutrient uptake by the fine roots with a corresponding dry matter investment as reported by Hummel et al. (2007). Root dry matter concentration (RDMC), as indicated by Shipley and Vu (2002), was used as a proxy to determine RTD in the study. This method has also been recommended by Birouste et al. (2014) as being relatively cheap, easy, and quick for determining RTD. The RTD was determined as root dry weight per unit root fresh weight.

4-2-7. Yield Component and Crop Productivity

The yield component was expressed in terms of fruit number per plant, fresh fruit weight per plant, and yield per area. Days to 50% flowering and fruiting were determined. Crop productivity (a measure of the crop’s harvestable yield in relation to the vegetative component) was determined as a ratio of the total fruit biomass to the plant’s total vegetative biomass.

$$\text{Crop Productivity} = \frac{\text{Total Harvested Fruit Biomass}}{\text{Total Vegetative Biomass}} = \frac{\text{Total Fruit Fresh Weight (g)}}{\text{Shoot + Root Fresh Weight (g)}}$$

4-2-8. Fruit Quality

Components of fruit quality measured were total soluble solids (TSS), titratable acidity (TA), and TSS/TA ratio. TSS and TA were measured using a K-BA100R spectrophotometer (Kubota, Yao, Japan) to scan the fruits. TSS/TA was determined as a fraction of TSS to TA.

4-2-9. Data Analysis

Data obtained was analyzed using the GenStat (Rothamsted Research, Harpenden, UK), and the least significant difference ($LSD_{0.05}$)) was used to separate the means.

4-2-10. Greenhouse Ambient Temperature and Humidity During the Cropping Cycle.

The daily readings for temperature and humidity were recorded.

4-3. Results

4-3-1. Greenhouse Ambient Temperature and Humidity During the Cropping Cycle.

The readings are shown in Figures 4-2 and 4-3. The data from 51 to 54 days of cultivation was not recorded by running out of battery.

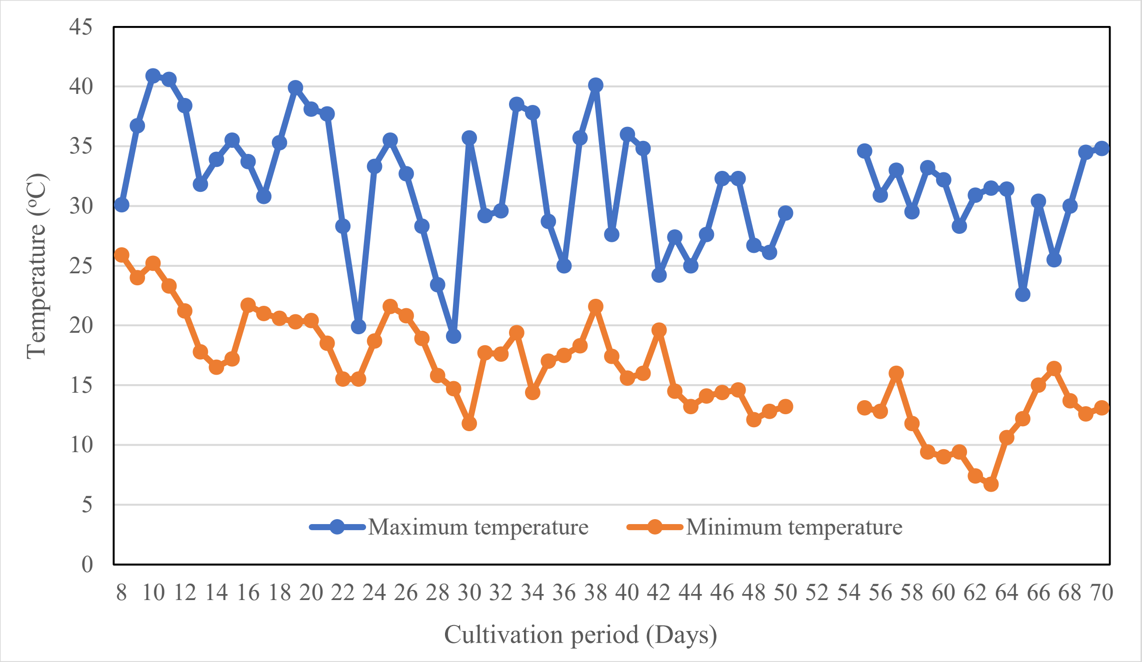

Figure 4-2. Ambient greenhouse temperature recorded during cultivation

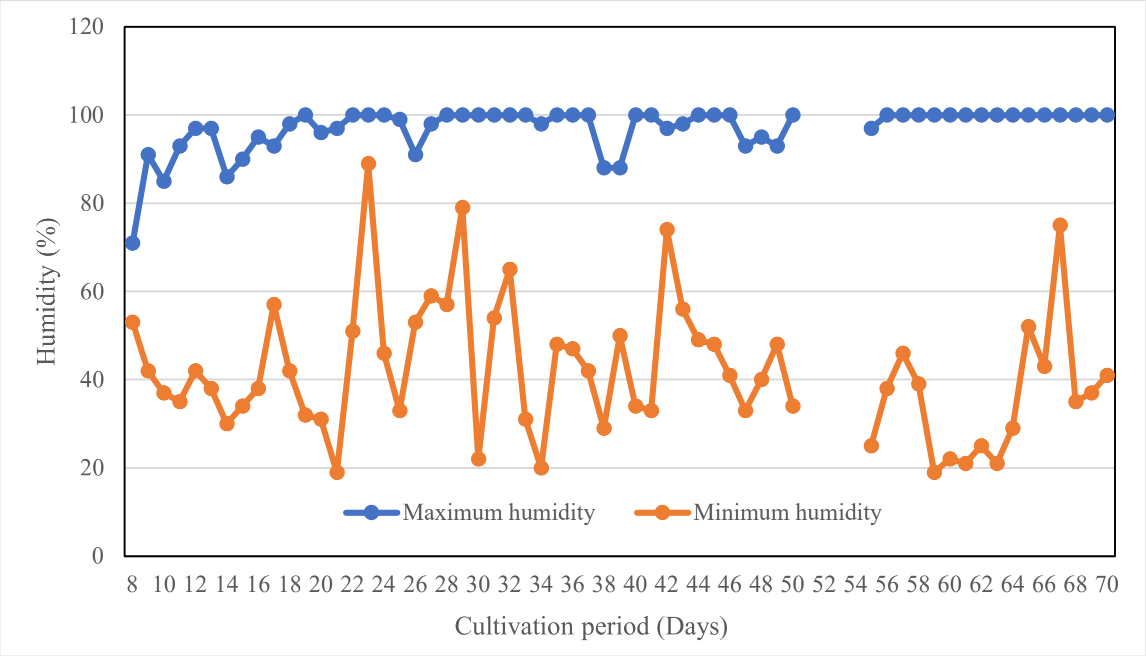

Figure 4-3. Ambient greenhouse humidity recorded during cultivation

4-3-2. Morphometrics

The two cultivars showed similar patterns of growth in terms of height. It was observed at 56 DAT that Momotaro plants grew significantly taller than Jaguar (Table 4-1). Momotaro York plants significantly produced thicker stems than Jaguar. More significant number of leaves was produced in Momotaro York than Jaguar plants. The chlorophyll content SPAD value was similar in both cultivars throughout the growth period.

Table 4-1. Morphological characteristics of tomato as influenced by low-node order pinching at high plant density (LN&HD).

a. Plant height (cm)	Days after transplanting			
Cultivar	14	28	42	56
Jaguar	60.2	106.9	128.9	135
Momotaro York	62.1	110.9	136.7	159.4
$LSD_{0.05}$	2.5	4.85	13.66	21.9
b. Girth (mm)				
Cultivar				
Jaguar	8.4	9.7	10.9	12
Momotaro York	9.7	11.1	12.9	13.9
$LSD_{0.05}$	1.99	1	1.03	2.69
c. Leaf number				
Cultivar				
Jaguar	10.5	13.4	15.9	17.2
Momotaro York	11.7	15.6	19.5	21.1
$LSD_{0.05}$	1.58	1.61	1.88	0.25
d. SPAD value				
Cultivar				
Jaguar	45.4	47.9	49.9	51.7
Momotaro York	44.3	48.3	50.3	52.0
$LSD_{0.05}$	2.28	2.74	2.7	2.0

$LSD_{0.05}$: least significant difference ($p < 0.05$).

4-3-3. Water and Nutrient Use Efficiencies

Figure 4-4a showed that the peak of water uptake for both cultivars was recorded between 37 and 39 DAT. Water uptake from the peak period to the first harvest was relatively higher in Momotaro York compared to Jaguar.

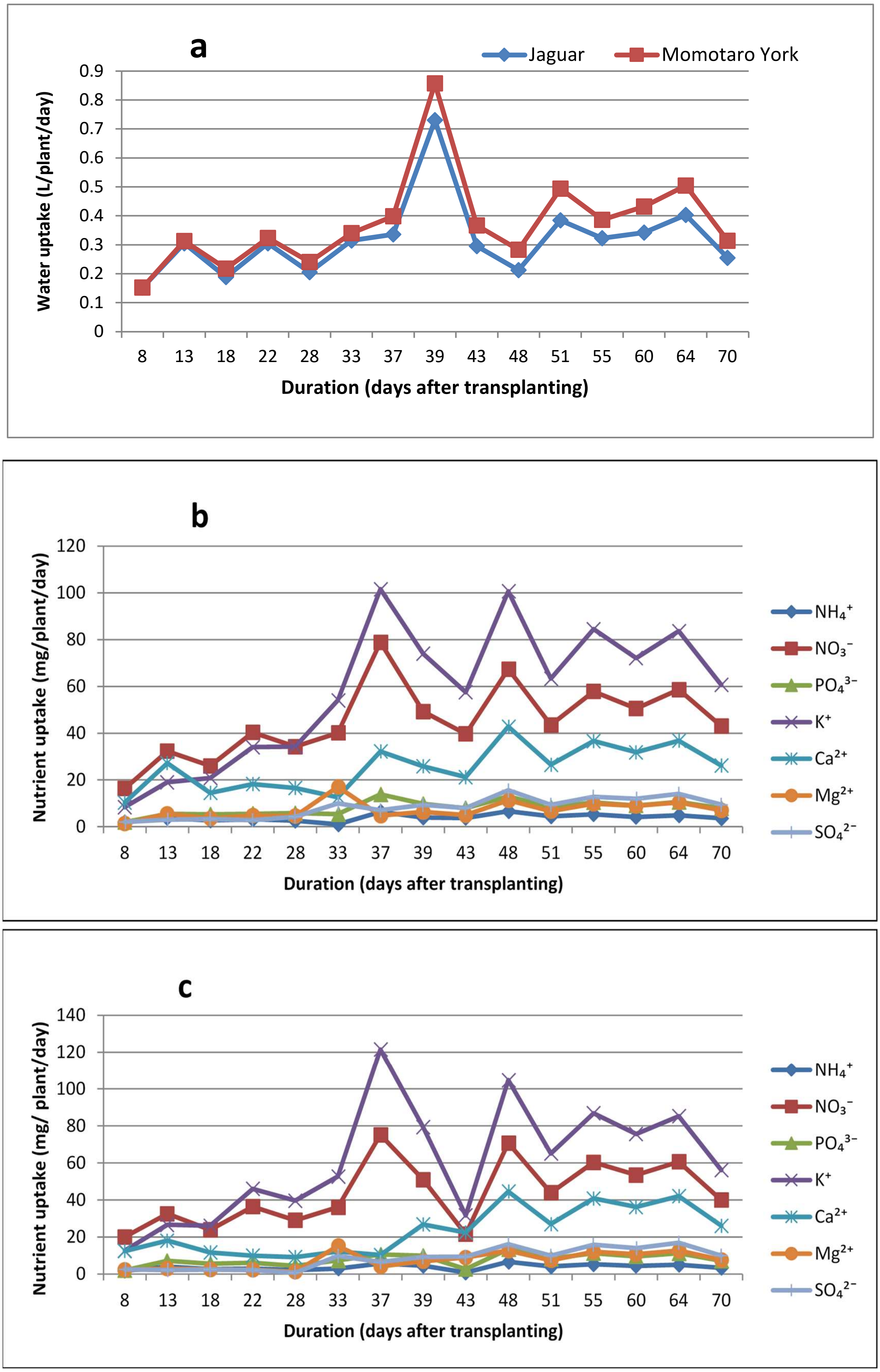

Figure 4-4. (a) Water uptake characteristics of Jaguar and Momotaro York, (b) nutrient uptake characteristics of Jaguar, and (**c**) nutrient uptake characteristics of Momotaro York

However, Table 4-2 showed that Jaguar recorded two times significantly higher WUE and NUE than Momotaro York at first harvest. Results from Figure 4-4b and c indicated that the highest nutrient uptake in the two cultivars occurred at 37 DAT for K and NO_3^-. Moreover, the uptake of Ca in Jaguar plants was higher than observed in Momotaro. Uptake of NO_3^- in Jaguar was twice that of Momotaro York at 43 DAT. Similarly, the uptake of Ca was relatively higher in Jaguar than in Momotaro York. The absorption of NH_4^+ was the lowest in the two cultivars. The trend in terms of nutrient uptake (for all the major nutrients) was similar in both cultivars.

Table 4-2. Water and nutrient use efficiencies of tomato at 70 days after transplanting (first harvest)

Cultivar	Fruit weight (kg plant^{-1})	WUE (kg kg^{-1})	NUE (kg kg^{-1})
Jaguar	0.658	0.033	221.1
Momotaro York	0.353	0.015	111.9
$LSD_{0.05}$	0.116	0.004	34.9

WUE: water use efficiency; NUE: nutrient use efficiency; $LSD_{0.05}$: least significant difference ($p < 0.05$).

4-3-4. Physiological Characteristics

The photosynthetic rate, conductance, and transpiration rate recorded were similar in the two cultivars (Table 4-3).

Table 4-3. Physiological response of tomato cultivars to LN&HD at 42 DAT.

Cultivar	Photosynthesis (µmol cm^{-2} s^{-1})	Conductance (mol cm^{-2} s^{-1})	Transpiration (mmol cm^{-2} s^{-1})
Jaguar	14.8	0.59	5.7
Momotaro	13.5	0.44	4.9
$LSD_{0.05}$	7.06	0.313	1.99

4-3-5. Dry Matter Partitioning

According to Table 4-4, Momotaro York recorded a higher leaf area, leaf, and stem dry DM than Jaguar over the growth period. However, the DM allocated to root was similar in both cultivars. Root- shoot ratio differed significantly in the two cultivars. In the last growth period, Momotaro York recorded a lower root-shoot ratio than Jaguar. DM allocated to fruit increased progressively in both cultivars over the growth period. However, Jaguar recorded a higher DM of 2.8 g allocated to fruit than Momotaro York at 42 DAT. The RTD observed was significantly higher in Momotaro York than in Jaguar.

Table 4-4. Dry matter partitioning and growth rate of tomato as influenced by LN&HD

		Days after transplanting				
Growth/DM		14	28	42	56	140
Leaf area (dm^2)	Jaguar	12.8	16.5	23.1	25.9	31.7
	Momotaro	14.7	24.1	27.3	36.1	48.2
	$LSD_{0.05}$	3.7	4.2	5.5	2.3	3.1
Plant DM (g plant^{-1})	Jaguar	16.6	31.5	68.9	88.3	215.5
	Momotaro	15.6	32.3	69.3	98.5	214.3
	$LSD_{0.05}$	3.9	6.6	9.9	11.5	40.2
Leaf DM (g plant^{-1})	Jaguar	6.2	12.7	16.2	19.7	41.6
	Momotaro	6.4	14.5	18.9	23.5	52.2
	$LSD_{0.05}$	1.4	2.5	1.9	2.3	9.9
Stem DM (g plant^{-1})	Jaguar	2.8	7.3	10.1	12.7	19.9
	Momotaro	3.1	8.7	13.4	14.8	28.9
	$LSD_{0.05}$	0.42	0.6	1.7	1.8	3.1
Root DM (g plant^{-1})	Jaguar	7.6	11.6	16.6	14.6	32.9
	Momotaro	6.0	9.1	14.9	14.6	32.0
	$LSD_{0.05}$	2.5	5.5	4	3.3	9.8
Root tissue density (g cm^{-3})	Jaguar					0.16
	Momotaro					0.18
	$LSD_{0.05}$					0.006
DMFr (g plant^{-1})	Jaguar			25.8	40.7	119.2
	Momotaro			23.0	46	99.6
	$LSD_{0.05}$			0.24	12.7	25.4
Root/Shoot ratio (g g^{-1})	Jaguar	0.84	0.58	0.62	0.47	0.56
	Momotaro	0.63	0.39	0.48	0.39	0.39
	$LSD_{0.05}$	0.19	0.25	0.03	0.2	0.07
RGR (g g^{-1} d^{-1})	Jaguar		0.046	0.056	0.018	0.0064
	Momotaro		0.052	0.055	0.025	0.0056
	$LSD_{0.05}$		0.03	0.02	0.0045	0.0021
NAR (g m^{-2} d^{-1})	Jaguar		0.073	0.14.	0.057	0.032
	Momotaro		0.063	0.1	0.067	0.019
	$LSD_{0.05}$		0.05	0.006	0.012	0.01

DM=dry matter; DMFr=dry matter allocated to fruits; RGR=relative growth rate; and NAR=net assimilation rate.

4-3-6. Yield Components and Crop Productivity

Table 4-5 showed that Jaguar flowered and fruited in three and five days, respectively, earlier than Momotaro York. However, the two cultivars were not significantly different in terms of fruit number or fruit weight per plant recorded. The fruit yield per area and crop productivity were not significantly different in both cultivars.

Table 4-5. Yield components of tomato as affected by LN&HD.

Cultivar	DTF	DTFr	Fruit number per plant	Fruit weight (kg plant^{-1})	Yield per area (kg m^{-2})	Crop productivity (g g^{-1})
Jaguar	11	17	15.8	2.5	9.6	1.4
Momotaro	14	22	16.2	2.6	10	1.3
LSD$_{0.05}$	2.9	1.4	7.01	0.6	2.12	0.25

DTF = days to 50% flowering; DTFr = days to 50% fruiting.

Figure 4-5 showed the appearance of mature fruits of Momotaro York and Jaguar grown in drip hydroponic system.

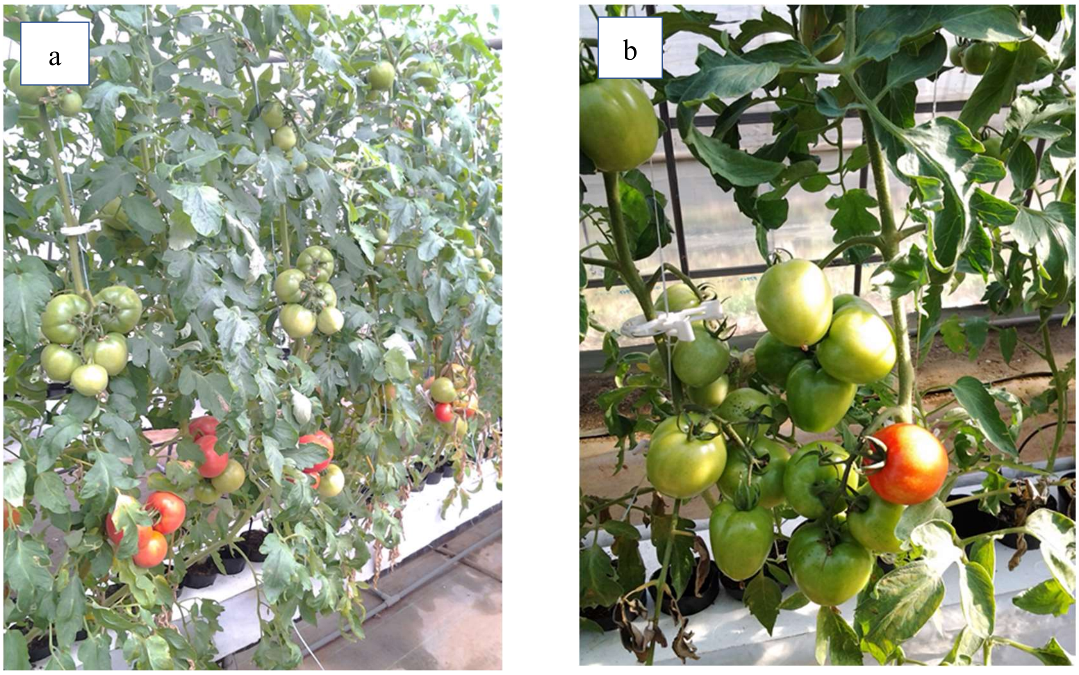

Figure 4-5. Mature fruits of (a) Momotaro York and (b) Jaguar grown in drip hydroponic system.

4-3-7. Fruit Quality

According to Table 4-6, the total soluble solids recorded was significantly higher in Momotaro York than in Jaguar. However, titratable acidity and TSS/TA ratio were similar in both cultivars.

Table 4-6. Fruit quality of tomato as influenced by LN&HD.

Cultivar	Total soluble solids (%Brix)	Titratable acidity (g L^{-1})	TSS/TA ratio
Jaguar	5.4	0.36	15.1
Momotaro	6.5	0.42	15.5
$LSD_{0.05}$	0.43	0.075	2.13

TSS: total soluble solids; TA: titratable acidity

4-4. Discussions

4-4-1. Morphometrics

Plant height at 56 DAT in Momotaro York was significantly higher than Jaguar, probably due to longer internode length in the former. Leaf numbers, as well as stem girth recorded in Momotaro plants, were markedly higher compared to the Jaguar plants. This may be due to an allocation of significantly higher plant biomass of 13.5% to stem in Momotaro as against 9.2% recorded in Jaguar. A similar observation has been reported where 12–13% dry mass was allocated to stem (Heuvelink, 1995).

4-4-2. Water and Nutrient Use Efficiencies

The peak of water uptake in both cultivars between 37 and 39 DAT was due to very high solar radiation in that period. This confirms that environmental factors could influence water uptake, as Wheeler et al., 1998 and Falah et al., 2010 have reported. The uptake of water in Momotaro was higher, probably due to higher leaf area and RTD. Tissue growth such as larger leaf area, thicker stems, and more young finer roots probably induced higher demand for water in Momotaro York than in Jaguar. However, water use was less efficient in Momotaro than in Jaguar. This was because more of the resource (water) was consumed towards vegetative growth at the expense of yield in Momotaro plants. Nutrient uptake in Momotaro York was significantly higher due to the more young, finer roots recorded.

High water and nutrient uptake, especially K^+ and NO_3^- could also be due to increased fruit load, reported by Koning (1989). At the peak of water uptake, a corresponding peak in nutrient uptake was observed as may be influenced by solar radiation. This implies that environmental factors strongly influence the uptake of K and N. Under a low substrate volume condition, plants recorded a preferential uptake characteristic for nutrients as might be influenced by environmental factors. This attribute could also be strongly influenced by crop variety. Plant uptake of NH_4^+ was the lowest compared to the other nutrients. This might be due to its initial low concentration in the nutrient solution, which was formulated purposely to check against BER. The order of preferential nutrient uptake characteristics in both cultivars was similar. Similar nutrient uptake characteristics have been reported by Weerakkody et al. (2011), and Kinoshita and Masuda (2011). Plants of Jaguar recorded higher Ca uptake than Momotaro York. This might be due to the higher root-shoot ratio recorded in Jaguar since the transpiration rate was similar in both cultivars. Absorption of Ca is dependent on water potential gradient and confirmed to be influenced by transpiration and growth rate of tissues (de Freitas et al., 2011). Additionally, Ca absorbed in Jaguar plants might have been used in producing much firmer fruits than Momotaro York (data not shown).

4-4-3. Growth Parameters

The leaf area recorded in Momotaro York was higher than in Jaguar. The difference in the leaf area might be attributed to more leaf numbers recorded in Momotaro York and the higher RTD. This, in effect, enhanced a higher uptake of water in Momotaro York. Also, the higher dry mass partitioned to fruits in Jaguar might have restricted the leaf area, as indicated in the findings of Higashide and Heuvelink (2009). Plants of Momotaro produced longer internode stems with a more significant number of leaves. This, in effect, showed that Momotaro York was more vegetative in growth than Jaguar. The higher root–shoot ratio in Jaguar showed an indication of better plant health and capacity for water and nutrient uptake.

In contrast, the lower root–shoot ratio recorded in Momotaro York could be due to a relatively higher uptake of nitrogen which probably favoured shoot growth. The allocation of higher plant dry weight to Jaguar fruit might also be due to the higher root–shoot ratio, which subsequently positively influenced the yield. Comparatively, Jaguar recorded a higher investment of DM into generative growth than Momotaro York. This result confirmed the findings of Higashide et al. (2012) that regardless of maximum photosynthetic rate with elevated CO_2, the DM component distributed to fruit in Momotaro York was reduced markedly. NAR differed significantly in the two cultivars at the last harvest. NAR was higher in Jaguar than Momotaro York in the same period. In that period, there was little fruit load in Jaguar due to an almost complete harvest. This, in turn, might have induced more partitioning of resources into vegetative growth in Jaguar; hence, the higher NAR. Additionally, the more significant number of leaves in Momotaro York might have induced inter-leaf shading. Momotaro plants recorded a higher RGR than Jaguar at 56 DAT due to a higher investment of resources towards vegetative growth.

4-4-4. Yield and Yield Components

Although Jaguar flowered and fruited earlier than Momotaro York, their yield characteristics were similar. Fruit yields of 28.8 and 30.0 kg m^{-2} per year were recorded in Jaguar and Momotaro York. This implies that Jaguar (with four months cultivation period) could be cultivated three times a year with a yield of 288 t ha^{-1} per year. This result is somewhat close to the yield of 360 t ha^{-1} per year reported by Higashide et al. (2015) as tomato yield in Japan under greenhouse conditions. In comparison, this yield result is 1.2–1.25 times less and 14.4–15 times more than current tomato yields recorded in Japan (greenhouse) and Ghana, respectively.

4-4-5. Fruit Quality

Plants of Momotaro York recorded significantly higher TSS compared to Jaguar plants. This difference might be due to the genetic attributes between the two cultivars. A previous study on Jaguar recorded a TSS value of 1.5 %Brix higher than that obtained in the present study. This difference might be attributed to the different hydroponic systems employed in the two studies.

The sub-irrigated hydroponic system induced a higher osmotic gradient; thus, increasing the TSS. In contrast, the present study instead recorded a larger fruit size at the expense of TSS. The TSS value recorded in Jaguar agrees with Nkansah et al. (2003), which reported the TSS of 3.5–5.6 %Brix for tomato grown in Ghana.

Chapter 5. Effect of Root Restriction on the Performance of Three-Truss-Cultivated Tomato in the Low-Node Pinching Order at High-Density Cultivation System.

5-1. Introduction

The abysmal tomato production in Ghana has been a congenital challenge. Therefore, efforts are geared toward increasing tomato yield sustainably, using a relatively affordable, adoptable, and practicable cultivation system. In recent times, a cost-effective cultivation system known as the low-node pinching order at high-density planting (LN&HD) has been widely adopted for tomato production (Takahashi et al., 2012; Tamai, 2014; Watanabe, 2006). The LN&HD is a cultivation system in which tomato plants are grown at high density and usually pinched (topped) between the first and the fourth node. Usually, the cultivation period is 70–120 days, while fruits are harvested between the first and the fourth truss. Plants' growing points are eventually pinched (topped) after the first, second, third, or fourth truss(es) is/are set. This practice reduces the cultivation period. Additionally, this cultivation system has been adopted to sustain a high yield and fruit quality of tomato in Japan (Johkan et al., 2013). Recently, the LN&HD has been recommended for Ghana to improve the productivity of tropical tomato cultivars at economic levels (Ayarna et al., 2020).

The LN&HD requires a small amount of substrate (low substrate volume) for growing plants. Incidentally, the total cost of production could be reduced with a low substrate volume. However, many other cultivation systems require a large amount of substrate. In effect, the total cost of production is increased (Pires et al., 2011). Substrate volume influences the crop's performance. Zhang et al. (2015) performed three-truss tomato cultivation in a 0.25 L pot. A yield of 1.3–1.5 kg per plant was reported. Pires et al. (2011) cultivated tomato in 5–10 L of a substrate in pots. Results showed that the yield and dry shoot mass were not affected by substrate volume. Substrate volume does not affect plant height (Saito et al., 2008). Different kinds of substrates have been used to cultivate tomato (Sampaio et al., 2008; Sezen et al. 2010). Coconut shell fiber (Cocopeat) is suggested to be more efficient for tomato production (Pires et al. 2009).

The LN&HD involves planting in a small-sized pot, which contains a small amount of substrate. When plants are grown (confined) in the pot, the roots become restricted (Mugnai et al., 2009). Root confinement in the pot induces a complete root restriction in that pot. This is because the root consummates its growth and other physiological activities strictly in the pot. However, the extent of root restriction reduces in Rockwool cultivation compared to the pot. Therefore, Rockwool cultivation techniques could be extrapolated. In this case, the Rockwool substrate is replaced with coconut shell fiber (Cocopeat). Therefore, root restriction in the Cocopeat is denoted as "Cocowool" in this study. The extent of root restriction affects the plant's performance in terms of growth, yield, and fruit quality. Root-zone restriction in vegetable cultivation is now widespread (Shi et al., 2008). Root-zone restriction reduces shoot growth and fruit yield (Pires et al., 2009), reduces plant height, leaf area, and dry plant mass (Mugnai and Al-Debei, 2011), increases the root-to-shoot ratio (Mugnai et al., 2000), and reduces root growth (Ismail and Noor 1996). In addition, root-restricted plants show a reduced shoot fresh weight and reduced fruit yield of tomato (Pires et al., 2009).

Tomato production, using the LN&HD cultivation system in some previous studies, adopted the nutrient film techniques. In recent studies, plants are now grown in pots specifically to induce root-zone restriction. The main objective of the root-zone restriction in those studies was to increase the fruit quality of tomato. However, increasing the fruit quality of tomato at the expense of yield is a potential drawback for adopting LN&HD in Ghana. Despite the primary focus on fruit quality, the yields obtained are usually fifteen times more than Ghana's yields. This study aimed to manipulate root restriction to increase the yield of tomato.

5-2. Materials and Methods

5-2-1. Site and Cultivation Conditions

The study was carried out at the greenhouse of the University of Ghana, Forest and Horticultural Crops Research Centre, Kade, (6°08'32.2"N 0°54'10.2"W), Ghana. The study spanned between April 21, 2019 and August 11, 2019. The Smart Sensor AR 867 thermo-hygrometer, Arco Science and Technology, China, was used to record the greenhouse ambient daily temperature characteristics.

5-2-2. The Recirculating Hydroponic System

The recirculating hydroponic system was constructed using locally available materials (Figure 5-1a). Materials obtained for the construction include plastic Tongue & Groove ceiling panels, coconut shell fiber, irrigation tubes and drippers, 12 V water pumps, 12 V car batteries, a timer (CN101A) switch, battery charger, wooden slabs, reserve tank, and plastic mulch. The total cost of these materials was 1042 US dollars.

5-2-3. Treatments

Four root restriction treatments were studied: (1) The first is confining plants in 1.0 L of the substrate in pots to induce complete root restriction (Figure 5-1b and 5-2a). (2) The second is confining other plants in 1.5 L of the substrate in pots (Figure 5-2a). The substrate volume is increased by 50% in this treatment. (3) The third is partial root restriction in Rockwool-like cultivation (Figure 5-1c and 5-2c). This treatment was termed “Cocowool.” The roots in the Cocowool are expected to initially undergo a partial root restriction in a 0.25 L pot. The roots are expected to grow further from the pot into the trough’s main substrate. (4) The fourth is cultivation in a trough with no root restriction. Each plant is exposed to 1.5 L of the substrate in the trough (Figure 5-2b).

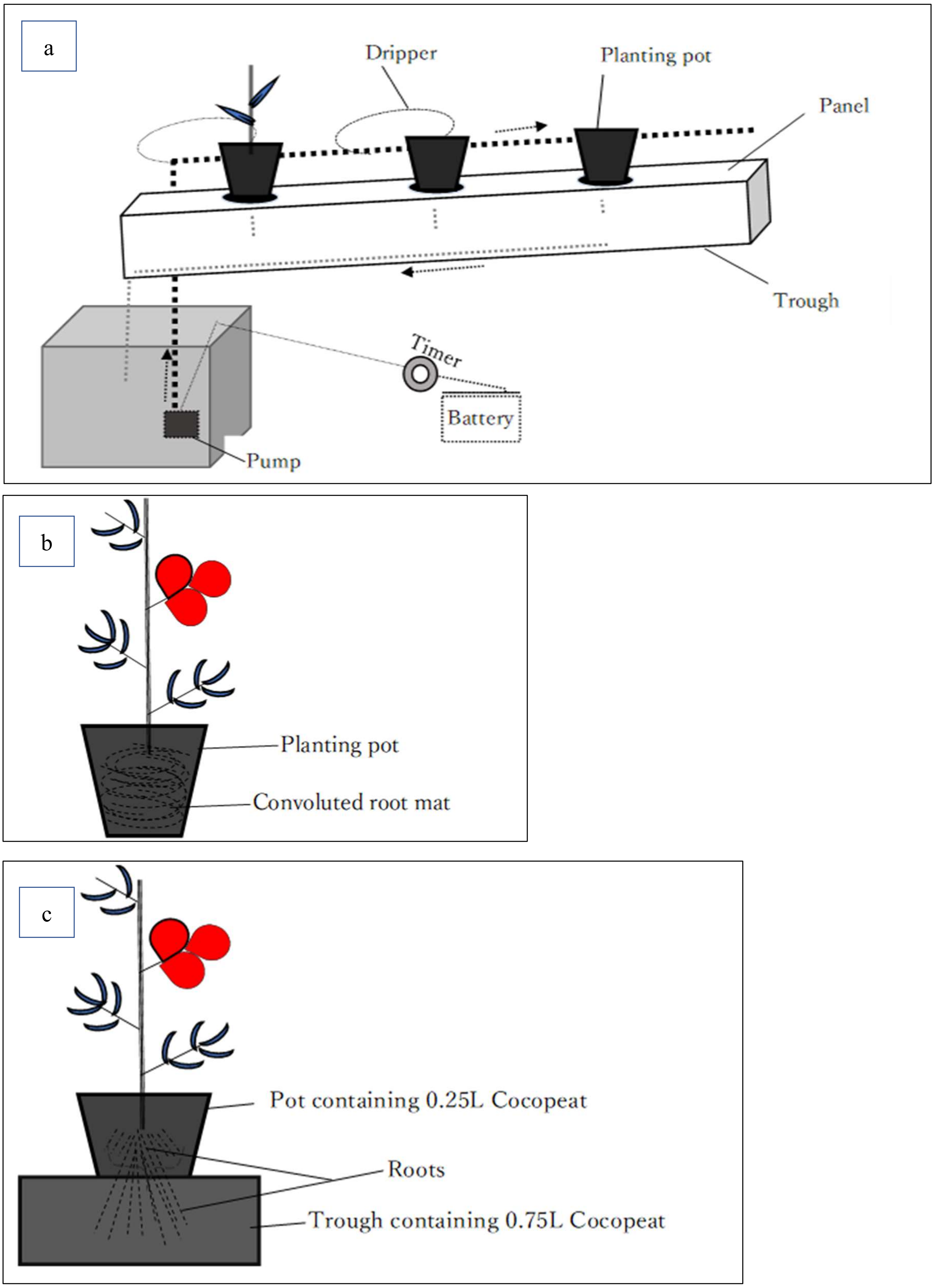

Figure 5-1. (a) Recirculating hydroponic system, (b) complete root restriction in 1.0–1.5L pot, and (c) Partial root restriction in Cocowool (0.25 L pot + 0.75 L trough)

Figure 5-2: (a) Complete root restriction, (b) No root restriction and (c) Partial root restriction.

5-2-4. Planting materials

Two cultivars of tomato were evaluated in the four root-restricted conditions. The two cultivars were Jaguar and Momotaro York, obtained from Techisem, Savanna Seed Company limited (Longué-Jumelles, France), and TAKII & Co., Ltd., (Kyoto, Japan).

5-2-5. Cultivation

The seeds were sown in cell trays using the coconut shell fiber (obtained from FibreWealth Limited, Tema, Ghana). Emerged seedlings were manually supplied with 0.1 S m^{-1} of a nutrient solution according to Enshi standard formula by the ebb and flow method. Seedlings were raised on a moveable bench in the greenhouse. The seedlings were transplanted on the third week after germination.

An automated recirculating drip system was set to feed the transplants. Plants were fed between 8:00 a.m. and 5:00 p.m. for two minutes per hour. The nutrient solution recipe adopted according to Enshi standard (Hori, 1966) was 0.7 mM NH_4-N, 8 mM NO_3-N, 1.3 mM PO_4-P, 4 mM K, 2 mM Ca, 1 mM Mg, 2 mM SO_4-S, 3 ppm Fe, 0.5 ppm B, 0.5 ppm Mn, 0.02 ppm Cu, 0.05 ppm Zn, 0.01 ppm Mo. The nutrients solution supplied was maintained at electrical conductivity of 0.12 S m^{-1} and pH 5.5–6.5. The spacing adopted was 1.2 by 0.2 m. Application of 1.0 mL L^{-1} 4-chlorophenoxyacetic acid was carried out on the flowers to enhance fruit set. Plants of the Jaguar cultivar were pinched (topped) on the seventh week after transplanting, while the Momotaro York plants were pinched on the eighth week after transplanting. Pinching was carried out on the third leaf above the third truss to discontinue further plant growth.

5-2-6. Data Collection

This study determined some growth parameters, yield, dry matter partitioning, and total soluble solids.

Plant height was measured between the second and the eighth weeks after transplanting (WAT). The plant's tallness was measured from the base to the plant's uppermost part with a ruler. Leaf number per plant was counted on the eighth week after transplanting. Leaves were detached from three randomly selected plants per treatment and photo-scanned with a photo camera. Leaf area was obtained using Lia25 software (https://www.agr.nagoya-u.ac.jp/~shinkan/LIA32/, accessed on 20 July 2019) to analyze the scanned leaves. The leaf area ratio (LAR) was calculated as the total leaf area divided by the total plant dry weight at eight WAT.

Plant dry matter production and partitioning to fruits were determined at the last harvest (16 WAT). Three plants were sampled at random from each treatment and destructively collected. Each sample (all plant parts and all harvested fruits) was oven-dried for seven days at 60 °C. The root-to-shoot ratio was determined as a ratio of the plant's root dry mass to the dry shoot mass. Root tissue density (RTD) was determined, according to the formula of Birouste et al. (2014), as the ratio between the plant's root dry weight and fresh root weight. RTD was determined at the last harvest.

Fruits were harvested from the three trusses per plant to determine the fruit number and fresh fruit weight. Yield per unit area was obtained as the fresh fruit weight per plant, multiplied by 4.1. The fruit's total soluble solids (TSS) were measured using the K-BA100R spectrophotometer (Kubota, Yao, Japan) to scan the fruits.

5-2-7. Experimental Design and Data Analysis

The experiment was laid out in a 2 × 4 factorial in randomized complete block design with three replications. Data collected were analyzed using GenStat (Rothamsted Research, Harpenden, UK), while Tukey's honest significant difference ($HSD_{(0.05)}$) was used to separate the means at $p < 0.05$.

5-2-8. Greenhouse ambient temperature recorded during cultivation

The ambient temperature in the greenhouse was recorded daily throughout the cultivation period.

5-3. Results

5-3-1. Greenhouse ambient temperature recorded during cultivation.

Daily readings for temperature in the greenhouse are shown in Figure 5-3.

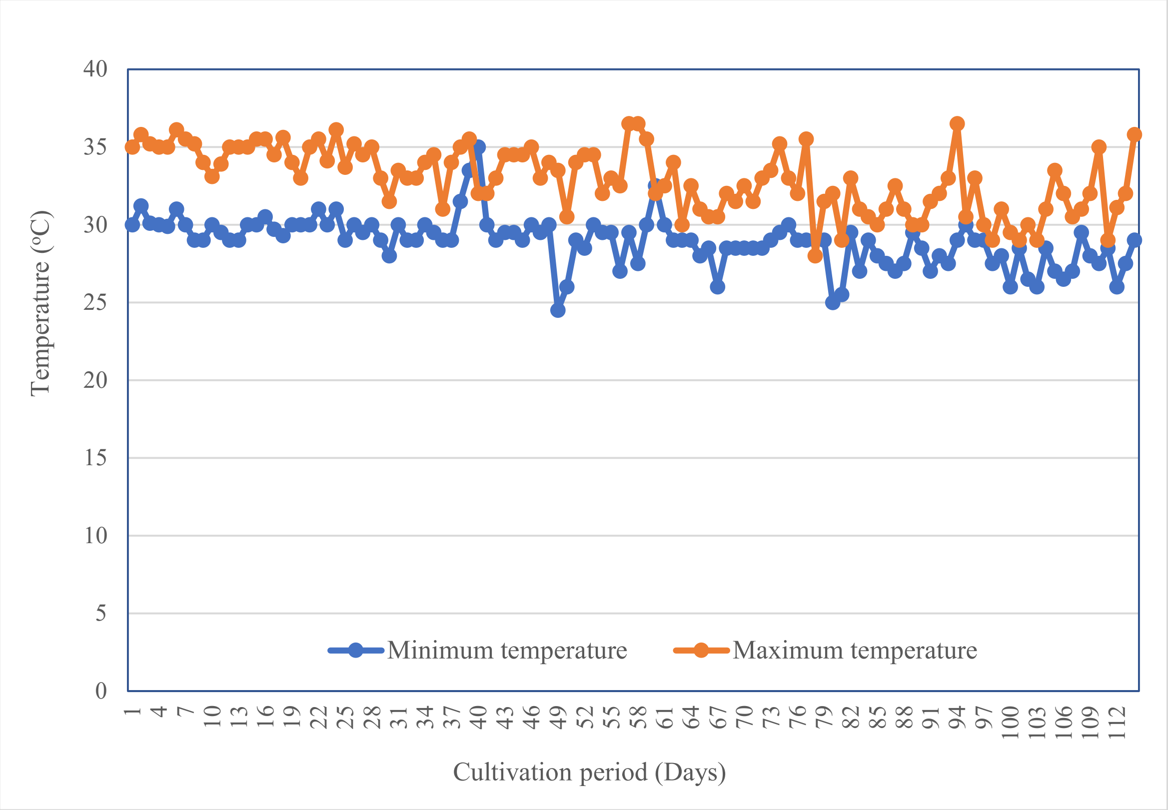

Figure 5-3: Greenhouse ambient temperature recorded during cultivation

5-3-2. Growth Parameters

Upon final pinching on the eighth week after transplanting, the Momotaro York plants were significantly taller than the Jaguar plants (Figure 5-4). Plant height was markedly influenced by root restriction. In the two cultivars, growth (plant height) was reduced for plants subjected to complete root restriction in the pots compared to the partial and the unrestricted plants.

The number of leaves varied significantly between the two cultivars at eight WAT. Momotaro York (MY) plants produced a more significant number of leaves than Jaguar (Table 5-1). Root restriction affected the number of leaves produced per plant significantly. Plants that received complete root restriction in the pots recorded fewer leaves than those in the other treatments. Root restriction with cultivar interactions affected leaf number. The unrestricted MY plants produced the highest number of leaves per plant.

The cultivars varied markedly in terms of leaf area (Table 5-1). MY recorded 946 cm^2 of leaf area more than Jaguar. The unrestricted plants recorded a higher leaf area than those in the other treatments. The highest leaf area was recorded in MY plants, which were unrestricted in the trough. For the two cultivars, complete root restriction reduced leaf area than partial or no root restriction.

The two cultivars differed in terms of leaf area ratio (Table 5-1). MY plants recorded 7.1 cm^2 g^{-1} of leaf area ratio more than Jaguar. The leaf area ratio recorded in the partial or unrestricted plants was higher than plants subjected to complete root restriction. Complete root restriction in the two cultivars had a lower leaf area ratio than the partial and the unrestricted.

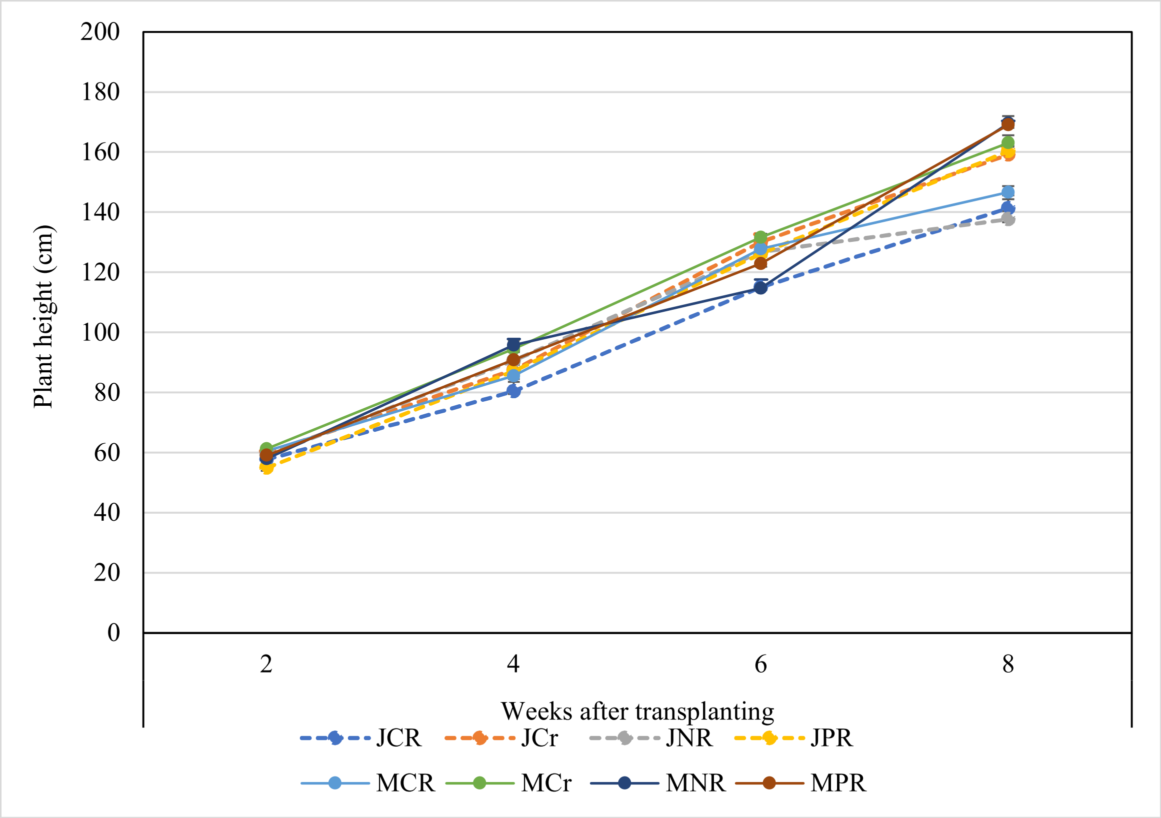

Figure 5-4. Plant height of tomato cultivars in response to root restriction J, M = Jaguar, Momotaro York cultivars; CR = complete root restriction in 1.0 L pot; Cr = complete root restriction in 1.5 L pot; PR = partial root restriction in Cocowool; NR = no root restriction; Every point represents the mean of three replications ±SE.

Table 5-1. Effect of root restriction (RR) on plant growth parameters of tomato cultivars at 8 weeks after transplanting (WAT)

Cultivar × RR Interactions	Leaf Number Per Plant		Leaf Area (cm^2 Plant^{-1})		Leaf Area Ratio (cm^2 g^{-1})	
	Jaguar	MY	Jaguar	MY	Jaguar	MY
Complete RR in 1.0 L pot	14.7 d	16.3 c	2779 f	3494 d	35.1 e	39.5 cd
Complete RR in 1.5 L pot	14.7 d	16.7 c	2784 f	3671 c	35.2 e	41.5 c
Partial RR in Cocowool	16.7 c	18.3 b	2969 e	3972 b	37.5 d	45.7 b
No RR in 1.5 L trough	17.3 bc	19.7 a	3040 e	4219 a	38.4 d	47.8 a
HSD$_{(0.05)}$	1.11		138.4		2.1	
Root restriction						
Complete RR in 1.0 L pot	15.5 c		3137 c		37.3 c	
Complete RR in 1.5 L pot	15.7 c		3227 c		38.3 c	
Partial RR in Cocowool	17.5 b		3471 b		41.6 b	
No RR in 1.5 L trough	18.5 a		3629 a		43.1 a	
HSD$_{(0.05)}$	0.8		97.8		1.5	
Cultivar						
Jaguar	15.8 b		2893 b		36.5 b	
Momotaro York	17.8 a		3839 a		43.6 a	
HSD$_{(0.05)}$	0.6		69.2		1.0	

MY = Momotaro York; WAT = weeks after transplanting; Figures followed by the same letter in a column are not significantly different according to Tukey's HSD at $p < 0.05$.

5-3-3. Dry Matter production and Partitioning

There was a variation in the total plant dry matter (TPDM) produced per plant in the cultivars (Table 5-2). The TPDM recorded in MY was 30.3 g more than Jaguar. Dry matter production was markedly affected by root restriction. Plants that received partial root restriction in the Cocowool produced the highest TPDM. Potted plants with a complete root restriction recorded the lowest TPDM. The interaction of root restriction with the cultivars influenced the TPDM significantly. For the Jaguar, the highest TPDM was observed in the plants that were partially root restricted in the Cocowool. Momotaro plants, which received complete root restrictions in the 1.0 L and the 1.5 L pots, showed no variation in TPDM production.

Dry matter partitioned to root (RDM) was influenced by root restriction (Table 5-2). Plants subjected to partial root restriction recorded the lowest RDM compared to other treatments.

Complete root restriction in the 1.0 and 1.5 L pots was similar in terms of RDM. RDM in the two cultivars was affected by the extent of root restriction. The cultivars recorded a low RDM when partially restricted in Cocowool. Plants that received complete root restriction in the pots showed a similar RDM. Conversely, plants cultivated in unrestricted conditions recorded the highest RDM in the two cultivars.

Dry matter partitioned to fruit in the two cultivars varied significantly. The MY plants partitioned 21.3 g more of dry matter to fruit than Jaguar (Table 5-2). Partitioning of dry matter to fruit in the complete root restricted plants reduced by 20 g and 13 g compared to the Cocowool and the trough cultivation. Dry matter allocation to fruit was affected markedly by root restriction and cultivar interactions. For Jaguar, plants partially root-restricted in Cocowool allocated more dry matter to fruit than the pots' complete root-restricted plants. Similarly, the dry matter allocated to fruit in the complete restricted MY plants was lower than the unrestricted plants.

The root-to-shoot ratio varied in the two cultivars (Table 5-2). Jaguar cultivar recorded 56 mg g^{-1} of root-to-shoot ratio more than MY. The root-to-shoot ratio was markedly influenced by root restriction. The unrestricted roots recorded the highest root-to-shoot ratio. However, plants that received complete root restriction in the pots recorded a higher root-to-shoot ratio than those partially restricted. The extent of root restriction influenced the root-to-shoot ratio in the two cultivars. Plants grown with partial root restriction for the two cultivars recorded the lowest root-to-shoot ratio than the other treatments.

The two cultivars varied markedly in terms of root tissue density (Table 5-2). The MY recorded 18.6 mg g^{-1} of root tissue density more than Jaguar. The extent of root restriction influenced the root tissue density of the plants. Plants that received partial root restriction in the Cocowool recorded the lowest root tissue density compared to the other treatments. The unrestricted plants recorded the highest root tissue density. In terms of an interaction between cultivars and root restriction, root tissue density was significantly affected. A partial root restriction of Jaguar plants in the Cocowool recorded the lowest root tissue density. The MY plants, on the other hand, responded differently to root restriction.

Table 5-2. Effect of root restriction (RR) on plant dry matter partitioning and root tissue density of tomato cultivars at 16 WAT.

Cultivar × RR Interactions	TPDM (g plant^{-1})		RDM (g plant^{-1})		FDM (g plant^{-1})		Root:Shoot Ratio (x10^{-3})		Root Tissue Density (mg g^{-1})	
	Jaguar	MY	Jaguar	MY	Jaguar	MY	Jaguar	MY	Jaguar	MY
Complete RR in 1.0 L pot	171.9 e	205.7 bc	31.5 c	31.7 c	83.6 d	108.8 b	561 b	488 cd	109.7 bc	106.4 bc
Complete RR in 1.5 L pot	174.1 e	212.6 ab	31.9 c	33.1 bc	85.8 d	115.8 ab	567 ab	520 bc	90.4 cd	116.2 b
Partial RR in Cocowool	202.2 c	218.8 a	26.8 d	27.9 d	116.9 a	121.9 a	457 d	404 e	74.7 d	96.3 c
No RR in 1.5 L trough	188.0 d	220.3 a	34.4 ab	35.9 a	100.1 c	123.4 a	609 a	560 b	117.2 b	147.4 a
HSD$_{(0.05)}$	8.6		2.1		7.3		45.1		19.9	
Root restriction (RR)										
Complete RR in 1.0 L pot	188.8 c		31.6 b		96.2 c		524 b		108.1 b	
Complete RR in 1.5 L pot	193.4 c		32.5 b		100.8 c		544 b		103.3 b	
Partial RR in Cocowool	210.5 a		27.3 c		118.6 a		431 c		85.6 c	
No RR in 1.5 L trough	204.3 b		35.2 a		111.8 b		585 a		132.3 a	
HSD$_{(0.05)}$	6.1		1.5		5.13		32		14.1	
Cultivar										
Jaguar	184.1 b		31.2 b		96.2 b		549 a		98 b	
Momotaro York	214.4 a		32.2 a		117.5 a		493 b		116.5 a	
HSD$_{(0.05)}$	4.3		1.0		3.6		23		10	

MY = Momotaro York; TPDM = total plant dry matter; RDM = dry matter partitioned to root; FDM = dry matter partitioned to fruit; WAT = weeks after transplanting; Figures followed by the same letter in a column are not significantly different according to Tukey's honest significant difference (HSD) at p <0.05.

The appearance of root development in partial root-restricted plants was shown in Figure 5-5. The roots have been well developed in Cocowool under root-restricted condition.

Figure 5-5. Young, finer roots formed in partial root-restricted plants

5-3-4. Yield and Total Soluble Solids

The number of fruits produced was not affected by cultivar, root restriction, or their interactions (Table 5-3).

The fresh fruit weight (yield) per unit area differed markedly in the two cultivars. The MY cultivar produced 800 g more yield than Jaguar. The unrestricted plants recorded the highest yield and followed by the partially restricted plants. Plants that received complete root restriction in pots produced the lowest yield. Cultivar and root restriction interaction affected the yield of tomato. The unrestricted or partially restricted Jaguar plants recorded the highest yield compared to those subjected to complete root restriction. The highest yield in the MY cultivar was recorded in the unrestricted plants and followed by the partially restricted plants.

The two cultivars varied in terms of total soluble solids (Table 5-3). Plants of MY produced higher total soluble solids than Jaguar. Plants cultivated in the pots with complete root restriction were higher in total soluble solids than the partial and the unrestricted. In the two cultivars, plants subjected to complete root restriction in pots were higher in total soluble solids than the partial or the unrestricted.

Table 5-3. Effect of root restriction (RR) on the yield and total soluble solids of tomato cultivars

Cultivar × RR Interactions	Fruit Number Plant^{-1}		Yield (kg m^{-2})		Total Soluble Solids (%Brix)	
	Jaguar	MY	Jaguar	MY	Jaguar	MY
Complete RR in 1.0 L pot	12.7 a	13.7 a	7.7 f	8.3 e	3.9 d	6.3 a
Complete RR in 1.5 L pot	12.7 a	13.3 a	8.0 ef	8.9 d	3.9 d	5.8 b
Partial RR in cocowool	12.7 a	13.3 a	9.2 cd	9.8 b	3.3 e	4.6 c
No RR in 1.5 L trough	12.7 a	13.3 a	9.4 c	10.6 a	3.3 e	4.8 c
HSD$_{(0.05}$)	2.0		0.4		0.4	
Root Restriction (RR)						
Complete RR in 1.0 L pot	13.2 a		8.2 c		5.1 a	
Complete RR in 1.5 L pot	12.7 a		8.3 c		4.9 a	
Partial RR in cocowool	13.0 a		9.5 b		4.0 b	
No RR in 1.5 L trough	13.0 a		10 a		4.1 b	
HSD$_{(0.05)}$	1.4		0.3		0.3	
Cultivar						
Jaguar	12.7 a		8.6 b		3.6 b	
Momotaro York	13.3 a		9.4 a		5.4 a	
HSD$_{(0.05)}$	1.0		0.2		0.2	

MY = Momotaro York; Figures followed by the same letter in a column are not significantly different according to Tukey's HSD at $p < 0.05$.

5-4. Discussions

5-4-1. Plant Growth Parameters

The difference in the plant height between the two cultivars was that Momotaro York (MY) had a longer internode length. Due to the longer internode length, pinching was delayed until the eighth week, hence the observed taller plants in the Momotaro York. Plants subjected to complete root restriction in the 1.0 and 1.5 L pots grew shorter than plants in the other treatments. This was associated with a reduced root growth, which consequently reduced the shoot growth. This result agreed with Mugnai and Al-Debei (2011), who reported that plant height significantly reduces with root restriction.

The leaf area recorded in MY was higher than that in Jaguar. MY produced a larger number of leaves with a broader leaf surface than Jaguar. The pots' complete root restriction reduced leaf area compared to the unrestricted and partially restricted plants. A 9–14% reduction in leaf area for plants subjected to complete root restriction was observed compared to the partial and the unrestricted. This study's findings agreed with Mugnai and Al-Debei (2011) and Kharkina et al. (1999), which reported that leaf area reduces with root restriction. The capacity for plants to accumulate dry matter (leaf area ratio) was higher in MY than in Jaguar. Such observation was due to a higher leaf area recorded in the former. The plant's capacity to accumulate dry matter decreased with an increase in the extent of root restriction. Complete root restriction reduced 10–14% of the plant's capacity to accumulate dry matter compared to partial or no root restriction.

5-4-2. Dry Matter Partitioning

MY plants were taller, with individual broader leaves and more significant leaf number. That accounted for the higher total plant dry matter (TPDM) production compared to Jaguar. The taller plants might have had a higher amount of photosynthates stored in the stems.

Complete root restriction in the 1.0 L and 1.5 L pots were similar in terms of TPDM produced. TPDM was reduced by 10% and 7% in the completely root-restricted plants compared to the partial and the unrestricted plants. This observation might be associated with a low sink demand in the completely restricted roots. A low sink demand is capable of reducing the accumulation of photosynthates in the sink organs. It was emphasized by Franck et al. (2006); Nakano et al. (2000); Scofield et al. (2009), and Velez-Ramirez et al. (2014) that assimilates produced in root-restricted plants exceed their utilization; therefore, the assimilates are usually stored in the leaves and the stems.

Conversely, it was observed that plants subjected to partial root restriction in the Cocowool method produced the highest TPDM compared to the other treatments. Initial root growth in the 0.25 L pot of the Cocowool method was very limited due to extreme initial root restriction. There was a further growth of young finer roots into the substrate of the underlying trough (Figure 5-5). The young finer roots did not add significantly to the root dry matter due to the low root tissue density. The finer roots are believed to be efficient in nutrient and water uptake for rapid plant expansion and more dry matter production in the Cocowool method. However, the two cultivars responded differently in terms of TPDM.

Partial root restriction in Cocowool reduced RDM compared to the complete and the unrestricted plants. Plants in the complete root restriction formed a larger mass of convoluted roots than in the partial. RDM was reduced by 17–20% for partial root restriction than the complete and the unrestricted. An increase in substrate volume by 50% in the pot condition did not affect RDM, as indicated in Ismail and Noor (1996).

Dry matter partitioned to MY’s fruit was 22% more than Jaguar due to the higher TPDM produced in the former. A 13–20% reduction in dry matter allocated to fruit was observed for complete root restriction in pots compared to the unrestricted or partial restriction in Cocowool. Cocowool cultivation, with a partial root restriction, favored the highest allocation of dry matter to fruit. That was an indication of a higher translocation of photosynthates to fruits as sink organs.

5-4-3. Yield and Total Soluble Solids

The yield per unit area in terms of fresh fruit weight recorded in MY was higher than in Jaguar. That was due to a higher partitioning of dry matter to fruit in the former. Dueck et al. (2010), Li et al. (2014), and Qian et al. (2012) stressed that tomato fruit sink strength differs at different stages of growth and in different cultivars. Plants subjected to complete root restriction in the 1.0 L and the 1.5 L pots encountered a yield reduction of 9–10% per unit area, compared to the other treatments. The unrestricted and the partially restricted plants might have impacted slight or partial limitations on the roots' growth, thus enhancing the translocation of more dry matter to fruit. Pires et al. (2011) indicated that root restriction did not affect tomato yield. Contrarily, results from this study showed that the yield of tomato increased with the extent of root restriction. The result supports the findings of Saito et al. (2008) that tomato yield decreases as root restriction increases. The yield recorded in this study was similar to 9.6–10.0 kg m^{-2} reported by Ayarna et al. (2020) in four-truss cultivation. This comparison further explains that root-zone restriction and the extent of restriction affect tomato yield.

The total soluble solids were higher in the MY fruit than Jaguar due to genetic discrepancies between the two cultivars. The MY might be one of the cultivars originally bred for high fruit quality in Japan (Higashide et al., 2012). Complete root restriction in the small pots recorded the highest total soluble solids compared to the other treatments. This might be attributed to a reduced root growth, which perhaps limits the uptake of water and nutrients. This study's results contradict the findings of Saito et al. (2008) that root restriction has no significant effect on tomato's total soluble solids. A 50% increase in the substrate volume of a 1.0 L pot with complete root restriction reduced the total soluble solids by 9%, depending on the cultivar. The total soluble solids of tomato, as influenced by root restriction, vary in different cultivars. The extent of root restriction influences the performance of tomato.

Chapter 6. General Conclusions

Results from the experiments showed that the low node pinching order at a high-density cultivation system (LN&HD) is efficient and cost-effective for increasing the yield of tomato cultivars in the tropics. The use of resources such as water, nutrient, and the substrate are highly efficient. Four-truss tomato cultivation at high-density planting increased the yield of tomato per unit area.

Under summer temperature (tropical) conditions, the heat-tolerant tomato cultivar was best suited for cultivation compared to the other cultivars. The Lebombo cultivar showed a high degree of heat tolerance and resistance to the incidence of blossom end rot (BER) but, the fruit yield was low. At high-density planting, fruit yield in the Jaguar cultivar was not significantly different from the HT. Notwithstanding, it is uneconomical to cultivate the former during extreme high-temperature conditions because there could be a yield loss of 51% due to BER. The implications of the results showed that the LN&HD could handle difficult cultivation situations in Ghana better than the Dutch system or the current cultivation practices in the country. The nutrient film technique (NFT) hydroponic system adopted in this study may be affordable since a small quantity of substrate is required with efficient use of water and nutrients. Tomato cultivation could therefore be practiced at least three times per year. A high-density planting of the HT could produce a fruit yield of 9.6 kg m^{-2} in a year. This study shows that high-density cultivation of the HT cultivar in NFT has the potential to increase Ghana's current tomato yield by 4.8 times. Under high tropical temperature conditions, further studies could be conducted using a drip hydroponic system with a slight increase in the substrate volume to assess the performance of the HT.

Incidentally, the LN&HD system has the potential of increasing the yield of tomato (Jaguar, pinched at the fourth node) by 14 times in Ghana during the rainy seasons. This is because temperatures recorded in the rainy seasons are relatively lower than that recorded in the summer. The Jaguar and Momotaro York cultivars are best for cultivation in the rainy seasons.

Cultivation of plants in different root restricted conditions affected tomato’s performance in terms of growth, dry mass partitioning, yield, and the total soluble solids. Complete root restriction of plants in small pots of 1.0–1.5 L of substrate reduced tomato yield by 9–10% per unit area. This root restriction method instead increased the total soluble solids at the expense of yield. A partial restriction of the root in 1.0 L of a substrate in a Cocowool method increased tomato yield at the total soluble solids’ expense. Additionally, the roots of plants cultivated in 1.5 L of a substrate in a trough (with no root restriction) increased tomato yield. Plants varied in response when cultivated in the same substrate root volume with differing root restriction degrees. Tomato cultivars responded differently to the cultivation conditions of root restriction. The low substrate volume cultivation of tomato can be adopted to increase Ghana’s tomato yield and reduce production costs compared to the country's current production practices, which adopt 10-15 L of substrate per plant. Also, this system's average daily plant water use was 0.28-0.34 L compared to soil/trough/bucket/plastic bag cultivation with 0.98 – 1.2 L. Furthermore, tropical areas with a shortage of water supply could adopt this cultivation system for efficient water use. The recirculating hydroponic system allows a high check against environmental pollution.

Incidentally, Ghana is currently placing more emphasis on the yield of tomato. Therefore, it is worthwhile to recommend the partial or no root restriction in Cocowool for increasing tomato yield at economic levels. The LN&HD is a valuable and effective tool for improving the yield of tomato cultivars grown in Ghana. However, with less root restriction (Cocowool cultivation), potential drawbacks of LN&HD are resolved. Farmers can adopt the LN&HD for sustainable tomato production in Ghana.

The lack of necessary materials, such as Styrofoam panels and troughs for the set-up, may make adopting the LN&HD technology difficult at first. Those materials, however, could be replaced by improvising locally available plastic T&G and wooden slabs. Additionally, the government of Ghana has approved the University of Ghana (UG) in collaboration with the Ministry of Food and Agriculture (MOFA) to train students and other stakeholders in protected cultivation. This has made it straightforward to spread the LN&HD technology through academic teaching and training.

Abstract

More tomatoes are consumed in Ghana than are produced. The lack of greenhouse technology, poor farming practices, and high-temperature stress, among other factors, contribute to the production gap. This work aimed to use state-of-the-art technology (cultivation system) to increase tomato cultivars' yield in the tropics at economic levels. Four studies were carried out. In the first study, three tomato cultivars (Jaguar, Lebombo, and Lindo) were evaluated for yield in a sub-irrigated hydroponic system during Japan's summer. Jaguar was selected as the desirable cultivar, even though its yield was reduced by 44.1% due to blossom end rot. Topping Jaguar at the fourth node in a closer spacing recorded the highest yield (93 t ha^{-1} y^{-1}) compared to the other cultivars. The cultivars' total soluble solids were higher in the sub-irrigated hydroponic system than that reported in Ghana. In study two, a heat-tolerant cultivar (Nkansah HT) was evaluated for fruit set, blossom end rot incidence, and yield under high summer temperature stress conditions. The heat-tolerant cultivar with Lebombo and Jaguar was grown in high and low plant densities under sub-irrigated hydroponic conditions. The three cultivars had more than 98% fruit set. The heat-tolerant with Lebombo was not affected by blossom end rot, but Jaguar recorded 51.7%. Because the heat-tolerant cultivar may be grown four times each year, it could produce 128 t ha^{-1} y^{-1} at a high plant density planting. In study three, Jaguar with Momotaro York was topped at the fourth node and evaluated in drip hydroponic conditions for resource use efficiency, crop productivity, and yield. Water use was more efficient (33 kg m^{-3}) than the current practice in Ghana (6.3 kg m^{-3}). This technology increased tomato yield (288-300 t ha^{-1} y^{-1}) compared to Ghana's current yield (8.6-180 t ha^{-1} y^{-1}). In study four, Jaguar and Momotaro York cultivars (topped at the third node) were evaluated for yield and fruit quality in (complete, partial, and no) root-restriction conditions. This study was conducted in Ghana under drip hydroponic conditions. Unrestricted plants recorded the

highest yield (300 t ha^{-1} y^{-1}), followed by partial root restriction (285 t ha^{-1} y^{-1}), while complete root restriction recorded the lowest (247.5 t ha^{-1} y^{-1}). This work showed that the LN&HD is efficient for increasing tomato cultivars' yield or fruit quality sustainably in the tropics at economic levels. During heat stress, the Nkansah HT is the best cultivar to grow. Partial or no root restriction is key to increasing the yield of tomato cultivars in the tropics.

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