Adv. Hort. Sci., 2025 39(2): 113-123
DOI: 10.36253/ahsc-17221
https://oaj.fupress.net/index.php/ahs

AHS
Advances in Horticultural Science

OPEN ACCESS

Effect of partial-extreme root restriction and nutrient solution concentration on the performance of hydroponically grown tomato

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Citation:
AYARNA A.W., TSUKAGOSHI S., SINTIM H.O., ULZEN J., AMISSAH J.N., BUKARI M., POKU S.A., TAKAGAKI M., LU N., ADJEI-NSIAH S., NKANSAH G.O., 2025 - *Effect of partial-extreme root restriction and nutrient solution concentration on the performance of hydroponically grown tomato.* - Adv. Hort. Sci., 39(2): 113-123.

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Author contribution:
Conceptualization: AWA, HOS, ST, JU, MB, ANS, JNA, SAP; Methodology: AWA, HOS, ST, GON, MT, JU, SAP, NL, MB, ANS; Formal analysis and investigation: AWA, HOS, ST, GON, JU, MT, NL, MB, ANS; Writing - original draft preparation: AWA, HOS, ST, GON, MT, NL, MB, ANS, JNA, JU; Writing - review and editing: AWA, HOS, ST, GON, MT, NL, MB, ANS, JNA, JU; Funding acquisition: AWA, HOS, ST, GON, MT, NL, MB, ANS, JNA, JA; Resources: AWA, ST, MT, NL, JNA, JU, ANS; Supervision: AWA, ST, GON, JNA, MT, NL, HOS, JU, ANS.

Data Availability Statement:
All relevant data are within the paper and its Supporting Information files.

Competing Interests:
The authors declare no conflict of interests.

Received for publication 24 January 2025
Accepted for publication 30 April 2025

Key words: Fruit quality, hydroponics, nutrient mix strength, photosynthesis, root confinement, water uptake.

Abstract: Tomato is a valuable agricultural commodity widely used across Africa with the potential to contribute to food and nutritional security. However, its yield, quality, and profitability are hindered by several challenges. The study evaluated the impact of partial-extreme root restriction and no root restriction on the performance of Jaguar tomato cultivar in two different nutrient solution concentrations: standard (2.4 dS m^{-1}) and half concentration (1.2 dS m^{-1}). The cultivation spanned three months using a recirculating hydroponic system arranged in a 2 x 2 factorial in a randomized complete block design with three replications. Data were collected on physio-morphological responses, yield, fruit quality, and water uptake. Plant growth, leaf gas exchange, yield, fruit quality, total water uptake, and root growth were significantly influenced by the nutrient solution concentration with root restriction. Particularly, plant growth, photosynthesis, total water use (52-62%), and yield were significantly reduced but fruit quality was improved by 25% compared to previous findings in Ghana. Conversely, the standard nutrient solution concentration without root restriction recorded the highest yield of 32.4 kg $m^{-2}y^{-1}$. These findings can serve as a manipulative hydroponic tool to increase tomato productivity and resource-use efficiency, especially in regions with limited water availability.

AHS - Firenze University Press
ISSN 1592-1573 (on line) - 0394-6169 (print)

1. Introduction

Tomato (*Solanum lycopersicum* L.) is a globally important crop, which is widely grown using various cultivation systems in different countries. The crop is cultivated for its edible fruits, which are used as a vegetable, for medicinal purposes, among others (Quinet *et al.*, 2019). The current target for growing tomatoes among industrialized countries is to meet medicinal and nutritional needs.

One of the most efficient but cost-effective cultivation system as adopted in some industrialized countries including Japan is the 'low node-order pinching at high-density planting' (LN&HD) (Watanabe, 2006; Takahashi *et al.,* 2012; Kinoshita *et al.*, 2014). This system adopts a low substrate volume at high-density cultivation plus pinching (topping) between the first and the fourth truss. With the low substrate volume, the plants are subjected to root restriction.

Vegetable production using root restriction is becoming popular especially where there is a need to adapt to adverse growing conditions, such as space constraints, limited water availability, and extreme temperatures (Shi *et al.,* 2008; Yamaura *et al.*, 2020). Root restriction is a cultivation strategy that involves deliberately confining plant roots within smaller container sizes with low substrate volume, thereby limiting their natural expansion. This technique influences root architecture and physiological processes, subsequently influencing overall plant growth, development, and resource allocation.

Root restriction affects the physiology of grown plants (Peterson and Krizek, 1992; Salisu *et al.*, 2018). The findings of Shi *et al.* (2008), Mugnai and Al-Debei (2011), and Campany *et al.* (2017) revealed that root restriction impairs the photosynthetic process due to a reduction in stomatal conductance. A reduction in photosynthesis in root-restricted plants might also be attributed to the physiological downregulation of photosynthetic activities due to high carbohydrate accumulation in the shoots of the plants (Pezeshki and Santo, 1998). However, other authors have indicated no significant differences in photosynthetic rate, stomatal conductance, intercellular CO_2 concentration, and transpiration between root-restricted and control plants (Kharkina *et al.,* 1999; Zakaria *et al.*, 2020). An earlier study by Hieke *et al.* (2002) showed that there was no inhibition of photosynthesis once there was new plant shoot regrowth.

Root restriction has also been reported to reduce plant growth (Ismail and Noor, 1966; Mugnai and Al-Debei, 2011; Ayarna *et al.*, 2021). Bihmidine *et al.* (2013) revealed that photosynthates were rather translocated into the stems of root-restricted pepper plants when the reproductive sinks were limited, leading to a yield reduction of 23%. Root restriction has also been reported to reduce fruit yield in tomato (Saito *et al.*, 2008).

Root restriction reduces water uptake (Saito *et al.*, 2008), leading to a subsequent reduction in transpiration (Bar-Tal *et al.*, 1994). Using root restriction can increase the sugar content of tomato (Li *et al.,* 2022). Root restriction has been reported to increase total sugar content due to reduced water uptake (Zakaria *et al.*, 2020). However, Saito *et al.* (2008) reported that root restriction did not affect the sugar content of tomato but reduced its water uptake.

Conventional root restriction confines the root system within the grow pot throughout the plant's growth cycle, limiting any further root expansion. In contrast, partial-extreme root restriction (characterized by a very low substrate volume, such as 0.25 L) utilizes a small (such as 0.25 L capacity) grow pot with an open base, initially imposing spatial confinement before allowing root extension beyond the restricted volume. After an initial phase of extreme root restriction in the small pot, this approach is expected to promote continuous root proliferation and growth, enhancing resource use efficiency and overall plant performance. Partial root restriction in tomato has been reported by Ayarna *et al.* (2021), who revealed that partially root-restricted plants produced more fine young roots, which were more efficient in the uptake of water and nutrients, subsequently increasing tomato yield.

In hydroponic cultivation systems, nutrients are supplied as a nutrient solution for plant uptake and utilization. Hoagland (1929) and Schwarz *et al.* (2002) emphasized that nutrient solution formulation should be synchronized with the cultivation system as well as the associated crop. Many nutrient solution formulations with appropriate concentrations have been developed to provide adequate nutrients for plant use (Jones, 1982; Sakamoto and Suzuki, 2020). However, improper or disproportionate formulation of nutrient solutions can adversely affect crop yield at any growth stage.

Many growers have attempted to use high amounts of fertilizer to achieve higher yields, but this practice has resulted in poor performance, with reduced yield and fruit quality (Zhang *et al.,* 2017). Nutrient solutions in hydroponic systems have low buffer capacity (Agius *et al.,* 2022), which can negatively impact plant growth. To prevent this, Lu *et al.* (2022) emphasized the need for judicious nutrient solution management. When the nutrient solution concentration (NSC) is relatively low (1.5 dS m^{-1}) in unrestricted root conditions, nutrient availability is inadequate, reducing fruit quality (Cliff *et al.,* 2012; Beesigamukama *et al.,* 2020) and causing low nutrient stress, which hampers plant growth, photosynthesis, and stomatal conductance (Beesigamukama *et al.,* 2020; Lu *et al.,* 2022). Conversely, while a high NSC (4.5 dS m^{-1}) leads to excess nutrient availability, causing stress and weakening plant growth (Anjum *et al.,* 2011; Rosadi *et al.,* 2014), it can also improve fruit quality by enhancing photosynthetic rate, transpiration rate, and stomatal conductance (Wang, 2017; Yang *et al.,* 2017). Meanwhile, tomato yield is not adversely affected at moderate NSC levels ranging from 1.5 to 2.4 dS m^{-1} (Veit-Köhler *et al.*, 1999).

Depending on the grower's objectives, nutrient solutions are maintained at 1.2 dS m^{-1} or higher. The Enshi nutrient solution recipe has been formulated for the cultivation of all vegetable crops at a standard concentration of 2.4 dS m^{-1}. A half-concentration of the Enshi recipe (1.2 dS m^{-1}) has been employed for the cultivation of root-restricted tomatoes in Japan with success. In general, extreme root restriction and higher nutrient solution concentration (NSC) are strategies specifically aimed at enhancing tomato fruit quality, albeit at the expense of yield.

Ghana consistently records low tomato yields and a low sugar content of 3.5-5.6% Brix (Nkansah *et al.,* 2003), making it crucial for implementing effective strategies to improve tomato yield and sugar content in the country. There are relatively few studies or reports on the effects of nutrient solution concentration on tomatoes grown under extreme but partially restricted-root conditions. The objective of this study was to evaluate the effect of partial-extreme root restriction and nutrient solution concentration on the performance of tomato, with the expectation that this approach would enhance the yield and fruit quality of tomato.

2. Materials and Methods

Experimental materials and procedures

The study was conducted between February and April 2024 at the University of Ghana's Forest and Horticultural Crops Research Centre at Kade, Ghana (43VX+GGG), in a greenhouse. Jaguar, a tropical tomato cultivar (Technisem Savanna Seed Company Limited-France) was used for the study. The greenhouse daily ambient temperature and humidity were recorded using thermorecorder-TR-72wb (T&D Holdings, Inc., Tokyo, Japan).

Two factors, namely root restriction of tomato and varied nutrient solutions of standard and halve concentrations, were evaluated. The tomato plants were subjected to partial-extreme root restriction (Fig. 1) as the main treatment, which was compared to the control treatment, with no root restriction. The adoption of extreme root restriction with a 0.20 L substrate volume in this study followed the method of Zhang *et al.* (2015), who subjected tomato plants to extreme root restriction using a 0.25 L extreme-low substrate volume in D-trays, geared toward improving fruit quality. However, the pattern of partial-extreme root restriction was after Ayarna *et al.* (2021). The cultivation of plants was carried out in

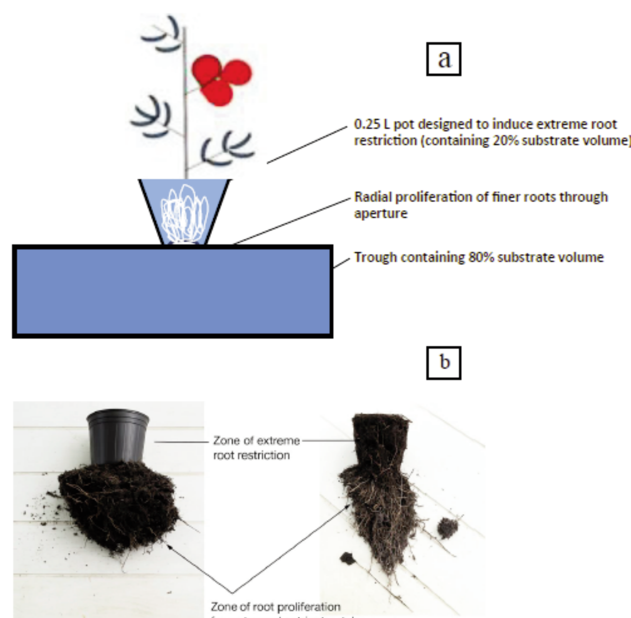

Fig. 1 - (a) Schematic representation of partial-extreme root restriction in hydroponic tomato cultivation. (b) Zones of extreme but partial root restriction and root proliferation.

Table 1 - Characterization of the adopted nutrient recipe in terms of macro- and micronutrients concentration

Nutrients	Standard nutrient solution concentration (2.4 dS m^{-1})
Macro-nutrients	mM
NH_4-N	1.3
NO_3-N	16
PO_4-P	1.3
K	8.0
Ca	4.0
Mg	2.0
SO_4-S	2.0
Micro-nutrients	ppm
Fe	3.0
Mn	0.5
Cu	0.02
Zn	0.05
Mo	0.01
B	0.5

a recirculating hydroponic system, using cocopeat as the substrate. A substrate volume of 1.0 L was used per plant in all treatments. In the root restriction treatment, the substrate was segmented into 0.20 L (pot) plus 0.80 L (trough). In the 0.20 L pot, the plants were subjected to an initial extreme root restriction; after which finer young roots were expected to proliferate into the 0.80 L trough for further water and nutrient absorption. The control treatment (unrestricted plant) was grown directly in the trough, containing 1.0 L of cocopeat.

A nutrient solution with a concentration of 2.4 dS m^{-1} was prepared following the Enshi recipe (Hori, 1966) as shown in Table 1. This concentration was then halved through dilution to 1.2 dS m^{-1}. The nutrient solutions (1.2 and 2.4 dS m^{-1}) were maintained within a pH of 5.5-6.5 and were delivered to the root zone of each plant using a drip system, in accordance with the adopted treatments.

Tomato seeds from the evaluated cultivar were sown in cell trays filled with cocopeat as the sowing medium. The seeds were then watered; and placed in a dark chamber under greenhouse conditions until they germinated. The germinated seedlings were supplied daily with a nutrient solution concentration of 0.5 dS m^{-1} using the Nutrient Film Technique until the third week, when they were ready for transplanting.

Twenty seedlings were transplanted into each treatment on the third week after seed germination at a spacing of 0.2 by 1.2 m. The set-up used an automated irrigation system to supply the tomato plants with nutrient solutions (1.2 or 2.4 dS m^{-1}) for 24 minutes daily, following treatment conditions from transplanting to harvest. After anthesis, 1.0 mL L^{-1} 4-Chlorophenoxyacetic acid was sprayed on the flowers every other day to enhance fruit set. Plants in each treatment were pinched at the last three leaves above the third truss to terminate further growth. Fifteen plants were tagged for data collection in each treatment.

Data collection and experimental design

Data were collected on the following parameters: morphological and physiological responses, yield, and water use efficiency. Morphological responses which were collected at 74 days after transplanting included: plant height, girth (measured below the third truss), and number of leaves per plant.

Physiological parameters were measured between 12:30 p.m. and 1:30 p.m. on the second and sixth weeks after transplanting. These included photosynthetic rate (Pr), transpiration (Tr), stomatal conductance (Gs), and the intercellular CO_2 concentration (Ci) using the LI-6400 Portable Photosynthesis System (LI-COR, Lincoln, Nebraska, USA). The leaves immediately below the first and third trusses were measured for photosynthetic parameters in the second and sixth weeks after transplanting, respectively.

All mature ripe fruits were harvested and counted to determine total and average fruit weights. The average fruit weight was determined as the ratio of the total weight to the total number of harvested fruits. Total sugar content (brix %) of the blended tomato juice was determined using the Atago™ pocket refractometer.

Plant water uptake was measured as the difference between total volume of nutrient solution supplied and the volume of nutrient solution left in the reservoir 14 h after daily irrigation. The total water used was measured as the total amount of nutrient solution absorbed per plant in the cultivation period (74 d). Water use efficiency was determined as the fruit yield per total water used per plant. After harvest, the fresh roots were cautiously extracted, wiped with a soft face towel and weighed. Additionally, portions of the root, which proliferated beyond the zone of extreme root restriction were collected and weight as the portion involved with water and nutrient uptake.

The experiment was laid out in a 2 x 2 factorial in a randomized complete block designed with three replications. Data collected were analyzed with the SISVAR version 5.6 (Ferreira, 2008) while the Tukey's honestly significant difference (HSD 0.05) was used to separate the means at $p<0.05$. Grouped graphs were constructed using GraphPad Prism version 8.0 for Windows, GraphPad Software, San Diego, California USA.

3. Results

Greenhouse ambient temperature and humidity

The greenhouse ambient humidity and temperature recorded during the study are shown in figures 2 a and b.

Plant morphological and physiological responses

Partial-extreme root restriction (R) and nutrient solution concentration (NSC) significantly $p<0.05$ affected the growth of tomato (Table 2). Plant height, girth, and leaf number decreased with root restriction compared to the unrestricted roots. Plant height and leaf number were significantly higher with the standard NSC compared to the half concentration.

According to figure 3, the photosynthetic rate (Pr) of the Jaguar tomato was not affected by root restriction at both nutrient concentrations, even though the stomatal conductance (Gs), transpiration (Tr) and intercellular CO_2 concentration (Ci) decreased significantly ($p<0.05$) at the vegetative phase (second week after transplanting) in the restricted treatment. Compared to the control, root restriction reduced Pr, Gs, Tr and Ci significantly at the reproductive phase (sixth week after transplanting) as shown in figure 4.

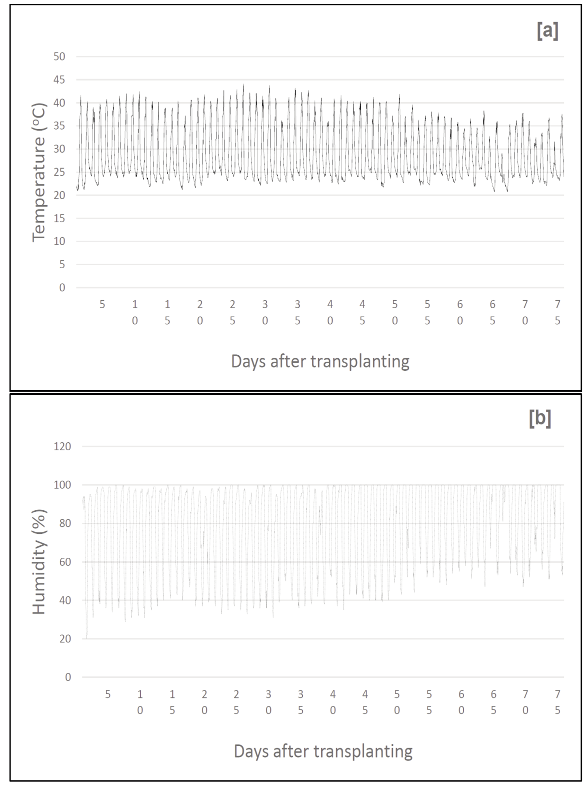

Fig. 2 - Greenhouse ambient humidity (a) and temperature (b) during the experiment.

The NSC had a significant impact on the physiological parameters of tomato during both the vegetative and reproductive growth stages (Figs. 3 and 4). The interaction effect of root restriction and NSC significantly affected the physiological response of tomato at the two stages of growth. The standard nutrient solution concentration with root restriction markedly reduced the Pr, Ci, and Gs compared to the unrestricted roots during the reproductive phase of growth (Fig. 3). In contrast, during the vegetative stage, root restriction under half-strength NSC increased Pr, while Ci, Gs, and Tr decreased relative to the no-restriction treatment (Fig. 3).

Table 2 - Morphological response of tomato to partial-extreme root restriction and nutrient solution concentration at 74 days after transplanting

Nutrient solution concentration	Root restriction	Plant height (cm)	Stem girth (mm)	Leaf number
Standard	Restricted	116.3 ± 0.88 aA	8.7 ± 0.07 Ab	11.7 ± 2.19 bB
	Unrestricted	117.3 ± 5.04 aB	11.7 ± 0.03 aA	20.0 ± 1.15 aA
Half concentration	Restricted	102.7 ± 2.30 bB	10.3 ± 0.07 aA	14.3 ± 0.33 bA
	Unrestricted	161.0 ± 6.81 aA	10.0 ± 0.06 aA	17.0 ± 0.41 aB
p-values		<0.01	0.045	0.048

Small letters compare means within root restriction, while capital letters compare means within nutrient solution concentration (NSC). Values in the same column or row followed by the same letters indicate no significant difference according to Tukey HSD (p<0.05).

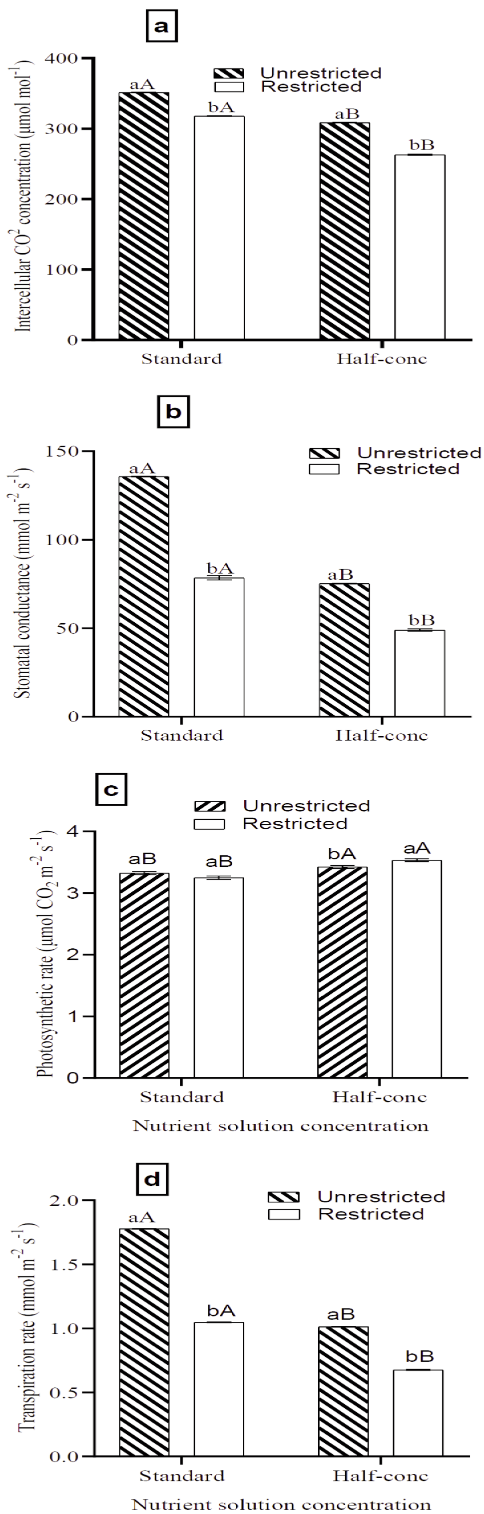

Fig. 3 - Physiological response of tomato to NSC and root restriction 2 weeks after transplanting. Lowercase letters compare means within NSC, while uppercase letters compare means among NSC And levels of R.

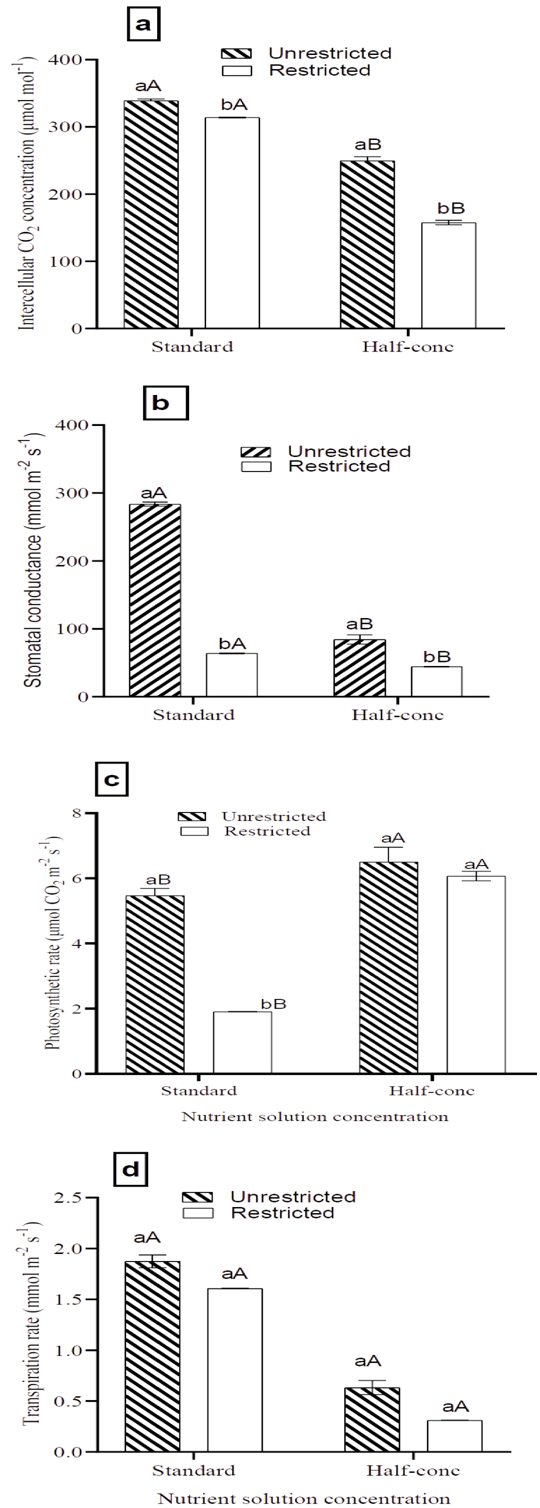

Fig. 4 - Physiological response of tomato to NSC and root restriction 6 weeks after transplanting. Lowercase letters compare means within NSC, while uppercase letters compare means among NSC and levels of R.

Yield and sugar content

Root restriction and the NSC did not significantly ($p<0.05$) affect the number of fruits produced per plant as shown in Table 3. The yield, average fruit weight, and sugar content (brix%) were markedly affected by root restriction and the NSC. Partial

Table 3 - Influence of root restriction and nutrient solution concentration on tomato yield, yield components, and sugar content

Parameter	Nutrient solution concentration	Restricted (Mean ± SE)	Unrestricted (Mean ± SE)	p-value
Fruit number per plant	Standard	11.3 ± 0.5 aA	13.0 ± 0.6 aA	0.1963
	Half-conc	13.3 ± 0.9 aA	12.9 ± 0.129 aA	
Yield (kg m⁻²)	Standard	3.88 ± 0.3 bB	8.08 ± 0.22 aA	<0.01
	Half-conc	7.32 ± 0.19 aA	7.08 ± 0.13 aB	
Average fruit weight (g)	Standard	76.2 ± 0.30 bB	149.6 ± 0.22 aA	0.0001
	Half-conc	140.6 ± 0.19 aA	130.9 ± 0.12 bB	
Brix (%)	Standard	6.97 ± 0.09 aA	4.57 ± 0.03 bB	<0.001
	Half-conc	4.43 ± 0.2 aB	4.2 ± 0.06 aB	

Small letters compare means within root restriction, while capital letters compare means within NSC and levels of root restriction. Values in the same column or row followed by the same letters indicate no significant difference according to Tukey HSD (p<0.05).

extreme root restriction with the standard concentration of nutrient solution significantly reduced the yield and the average fruit weight of the cultivar compared to the other treatments. Unrestricted roots grown in the standard NSC had the highest yield of 8.1 kg m^{-2} with a low sugar content of 4.6%. Conversely, extreme partially restricted roots grown in the same NSC recorded the highest sugar content of 6.9% but with the lowest yield of 3.63 kg m^{-2}.

Water uptake trend and water use efficiency, and root growth characteristics

Figure 5 illustrates that the trend of water uptake among the treatments were similar between day 1 and 28 but diverged on the 30th day after transplanting. Water uptake in the restricted roots cultivated in the standard concentration was generally lower than the other treatments throughout the cultivation period. However, peak of water uptake in the other treatments was observed between the 33rd and 56th day after transplanting.

The total water use (TWU) and its efficiency were significantly (p<0.05) affected by root restriction as shown in Table 4. Total water use was markedly reduced in restricted roots compared to unrestricted roots, leading to a higher water use efficiency in the former. The amount of water used was influenced significantly by the concentration of nutrient solution. Standard NSC reduced water uptake than the half concentration.

Root growth (fresh weight) was markedly affected by root restriction and NSC. Root growth was markedly reduced by root restriction compared to the unrestricted. The standard NSC had a significant reducing effect on root growth than the half concentration. Root proliferation (zone of root growth beyond the zone of extreme partial root restriction) was reduced with the standard (high) NSC.

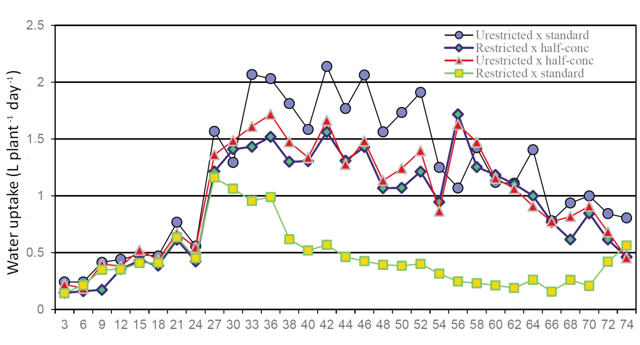

Fig. 5 - Influence of partial root restriction and nutrient solution concentration on the trend of tomato daily water uptake.

4. Discussion and Conclusions

Plant root restriction is a cultivation technique in horticulture where roots are confined within a limited space and this subsequently limits the plant growth potential. Numerous reports indicate that this technique generally results in improved fruit quality (sugar accumulation, anthocyanin enrichment) despite the reduction in photosynthesis (Wu *et al.* 2018; Zakaria *et al.,* 2020). The adoption of high nutrient solution concentrations in soilless culture has been used singly as efforts to increase

Table 4 - Influence of root restriction and nutrient solution concentration (NSC) on water uptake and water use efficiency

Nutrient solution concentration	Restricted		Unrestricted
Total water uptake (l plant $^{-1}$)			
Standard	13.9 ± 0.058 bB		36.93 ± 0.14 aA
Half concentration	28.9 ± 0.46 aB		31.0 ± 0.48 bA
p-value		<0.001	
Water use efficiency (g fresh fruit weight L^{-1})			
Standard	259.2 ± 0.058 aA		218.8 ± 0.145 aA
Half concentration	253.3 ± 0.463 aA		228.5 ± 0.481 aA
p-value		0.563	
Root fresh weight (g plant $^{-1}$)			
Standard	31.67 ± 1.67 bB		62.67 ± 1.15 bA
Half concentration	56.00 ± 1.73 aB		70.00 ± 1.45 aA
p-value		0.002	
Proliferation root mass (% fresh weight plant^{-1})			
Standard	5.00 ± 1.15 b (16.1%)		
Half concentration	12.67 ± 0.33 a (22.6%)		
p-value	0.034		

Small letters compare means within root restriction, while capital letters compare means within NSC and levels of root restriction. Values in the same column followed by the same letters indicate no significant difference according to Tukey HSD (p<0.05).

fruit quality but usage coupled with root restriction remains unclear hence this study tried to obtain plausible explanations to the mechanisms that influences plant growth, yield, fruit quality and water uptake under these two factors i.e., root restriction and nutrient solution concentration.

Physio-morphological responses to plant root-restrictions and NSC

In this study, plant root-restriction reduced the growth of tomato, which has been confirmed in the finding of Kasai *et al.* (2012). The work of Zakaria *et al.* (2020) on chili pepper reported a 14% reduction in plant height due to root restriction. However, the findings of this work showed that partial-extreme root restriction of tomato reduced plant height by 21% compared to the control. Although these comparisons are from two different crops, the trends of the impact of root restriction are similar. The differences in absolute percentage change might be due to the extent of root mass reduction because of the initial extreme restriction imposed on tomato roots. Tomato plants subjected to root restriction under the standard concentration also showed reduced plant growth in terms of height, girth, and leaf number. A high NSC is known to impair water uptake (Ding *et al.,* 2018), and in partial extreme root-restricted conditions this might have influenced the growth reduction.

The tomato plants with extreme partially restricted roots showed decreased leaf gas exchange compared to the control plants six weeks after transplanting. An impairment in photosynthetic rate due to a reduction in stomatal conductance in root-restricted plants has been confirmed in the works of Shi *et al.* (2008), Mugnai and Al-Debei (2011), and Campany *et al.* (2017). Nevertheless, the outcomes of this study differed from Zakaria *et al.* (2020) and Santos *et al.* (2022) findings, which indicated that leaf gas exchange of chili pepper and jenipapo was not significantly affected by root restriction.

The standard nutrient solution concentration, with or without root restriction, induced a reduction in the photosynthetic rate of tomato compared to the half-strength, despite an increase in the Tr, Gs, and Ci. This finding could be attributed to downregulation of photosynthetic rate due to water stress, particularly in the partially extreme root-restricted plants, which demonstrated sink limitation resulting from a decrease in root mass. The findings of Beesigamukama *et al.* (2020) suggested that a low NSC induces nutrient stress hence, photosynthetic rate is significantly reduced. The findings of this study, however, showed that the photosynthetic rate of tomato could be reduced by 41% when grown in the standard nutrient solution concentration of 2.4 dS m^{-1}.

Furthermore, the findings of the study revealed that partial extreme root-restricted tomato plants, which were grown in the standard nutrient solution concentration showed a 65-70% reduction (downregulation) in the photosynthetic rate at the generative phase. In other studies, Lu *et al.* (2022) reported that a NSC of 1.5 dS m^{-1} could induce nutrient stress, reducing the rate of photosynthesis of cherry tomato, but they reiterate that the rate of photosynthesis can only be maintained at a concentration of 3.0-5.0 dS m^{-1}. On the other hand, this present study found that a NSC of 1.2 dS m^{-1} was sufficient to provide necessary nutrients to plants without causing any nutrient stress, as plants in the partially extreme restricted root treatment did not show signs of nutrient deficiency. Additionally, when the 1.2 dS m^{-1} NSC is doubled, the cultivar turned out with a divergent response when the roots were restricted.

Yield, fruit quality, and water uptake under plant root-restriction and NSC

The tomato yield decreased significantly by 35.4% due to partial extreme root restriction. This restriction inhibited root growth, leading to a diminished sink capacity and ultimately inducing a downregulation of photosynthesis. Bihmidine *et al.* (2013) found that pepper experienced a 23% decrease in yield due to root restriction. Other studies (Saito, *et al.*, 2008; Ayarna *et al.*, 2021) have also reported yield reductions in tomatoes due to root restriction. Partial extreme root restriction, in this study, increased the fruit quality (sugar content) of tomato by 52%, which is a 25% improvement over values previously recorded in Ghana (Nkansah *et al.*, 2003). The findings of Li *et al.* (2022) also reported that root restriction increased the sugar content of tomatoes.

Tomato fruits from the standard NSC had higher sugar content without affecting yield. This finding aligns with previous studies by Veit-köhler *et al.* (1999) and Wang (2017). Findings from this study revealed that partial-extreme root restriction with the standard NSC increased the sugar content of tomato while the yield was markedly reduced. These two technical hydroponic tools could be employed to increase the sugar content of tomatoes, especially, the cherry type. Furthermore, the synergistic effect of root restriction and standard nutrient solution concentration generally reduced water uptake in the tomato cultivar. The reduction in water uptake was markedly lower at the generative phase of growth. Osmotic stress in the root environment most probably accounts for the remarkable reduced water uptake in the tomato plants that were subjected to root restriction in the standard NSC. After the initial extreme root restriction, subsequent root proliferation produced a smaller root mass with a higher absorptive surface area per unit due to the presence of finer, younger roots. However, these roots remain generally disadvantaged by a reduced overall absorptive capacity compared to unrestricted roots. Under these conditions, an NSC of 2.4 dS m^{-1} was sufficient to induce water stress, leading to reduced water uptake. This observation is consistent with the findings of Saito *et al.* (2008) and Liu *et al.* (2023), who reported that root restriction under high NSC conditions enhanced tomato fruit quality but reduced fruit size due to water stress. Partial-extreme root restriction of tomato reduced total water uptake by 37% compared to the control plants. Water use was more efficient in the partially extreme root-restricted plants however, the yield was negatively affected because of a reduced photosynthetic rate with low dry matter production. The findings of Ismael and Dalia (1995) and Bar-Tal *et al.* (1994) confirmed that water uptake reduces with root restriction in tomato. A high NSC significantly decreased the uptake of water, and yield of tomato when roots are extremely confined (restricted).

In an environment with extreme partial root restriction, the standard NSC, which denotes a higher nutrient solution concentration, induced a significant reduction in root growth. This suggests that the concentration of the nutrient solution has a notable impact on root growth in such conditions. In the environment with extreme root restriction, our observations indicate that 16.1% portion of root mass was present in the standard concentration of the nutrient solution, while 22.6% was evident in the half concentration. Under extreme partial root-restricted conditions, only 16-22% of the root mass was found to be most probably actively involved in water and nutrient uptake. Reduced root growth indicates a decrease in the plant sink structure (capacity), which influenced the downregulation of photosynthesis and yield reduction.

Under normal growth conditions, slight changes in NSC may not have an adverse effect on tomato performance, unless the associated roots are restricted. When roots are extremely but partially restricted in their growth under the same nutrient solution concentration, there is a trade-off between sugar content and yield. In the low node order pinching at high density planting, partial-extreme root restriction and NSC are effective manipulative hydroponic tools for comparatively increasing the yield and fruit quality of tomato while conserving water. In general, the productivity of tomatoes could be improved at a cost-effective level since the cultivation system involves the use of low substrate volume. This growing system can allow four cultivation cycles of tomato per year. The sugar content of tomatoes grown in Ghana could be improved by 25% with a corresponding yield of 14.5 kg m^{-2} y^{-1}. Cherry tomatoes could also be grown in these conditions to improve fruit quality while significantly reducing water use. Additionally, geographical areas with limited water resources could benefit from the use of this tomato cultivation system. While maintaining the fruit quality within the reported range, the yield of tomato could be increased to 32.4 kg m^{-2} y^{-1} when the standard NSC without root restriction is adopted under greenhouse conditions.

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