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Integrated Fertilizer, Irrigation and Variety Management Strategies for Sustainable Greenhouse Tomato Production in Tropical Climates

Yayra K. Agbemabiese[1,2*], Abdul-Halim Abubakari[1,3], Israel K. Dzomeku[1,4]

[1]West African Center for Water, Irrigation and Sustainable Agriculture (WACWISA), University for Development Studies, P. O. Box TL 1882, Tamale, Ghana
[2]Department of Agricultural Engineering, University for Development Studies, P. O. Box TL 1882, Tamale, Ghana
[3]Department of Horticulture, University for Development Studies, P. O. Box TL 1882, Tamale, Ghana
[4]Department of Crop Science, University for Development Studies, P. O. Box TL 1882, Tamale, Ghana.

**Correspondence: yayra92@gmail.com*

Abstract

Optimizing nutrient supply, irrigation and varietal selection is critical for maximizing greenhouse tomato productivity in tropical climates. This study assessed the combined effects of fertilizer levels, irrigation water requirements, and variety on greenhouse tomato growth characteristics, rootzone EC and pH, yield, and potassium use efficiency under contrasting micro-climates. A split-split plot design compared three (3) levels of fertilizer (F1: 100 %, F2: 80 %, F3: 60 %), three levels of irrigation water requirement (I1: 100 %, I2: 80 %, I3: 60 %) and two tomato varieties (V1: Jalila F1, V2: Yetty F1) across contrasting micro-climates. Variations in irrigation levels notably affected EC and pH, with micro-climate 2 exhibiting more pronounced responses. Optimal irrigation and fertilization generally improved plant height, stem girth, chlorophyll content, and biomass (leaf, stem and side-shoot), in Jalila F1 and Yetty F1. Yield and potassium use efficiency were maximized under the combination of 100 % fertilizer and 100 % irrigation, with notable variations observed across micro-climates. In micro-climate 1, Jalila F1, treated with 100 % fertilizer level and 100 % irrigation requirement, had the highest yield (101.6 t/ha), and Yetty F1, treated with 100 % fertilizer level and 100 % irrigation water requirement, had the highest yield in micro-climate 2 (91.7 t/ha). The findings show that integrating moderate fertilization, full irrigation, appropriate variety selection and micro-climate can simultaneously improve yield and quality and optimize potassium use efficiency. Such strategies are essential for sustainable intensification of greenhouse tomato production in water-limited tropical environments.

Keywords: *Fertigation, Greenhouse, Soilless, Micro-climate, Potassium Use Efficiency*

Introduction

Tomato (*Lycopersicon esculentum* L.) is an essential component of the human diet worldwide (Peralta and Spooner, 2007) and ranks as the second most important vegetable after potato. According to Willcox *et al.* (2003), tomatoes are rich in vitamins A and C, potassium, fiber, carotenoids, and antioxidants such as lycopene. These bioactive compounds help prevent various cancers and cardiovascular diseases, strengthen bones, and improve skin health (Burton-Freeman and Reimers, 2011). In Ghana, the rapid decline of the tomato industry since the early 2000s has been attributed to a complex combination of biotic and abiotic challenges (Robinson and Kolavalli, 2010). Major tomato-producing areas in the Northern regions have experienced an accumulation of soil nematodes and a sharp increase in fungal, bacterial, viral and other pests collectively referred to as the "Tomato Disease Complex" (Baba *et al.,* 2013; Vigbedor, 2019). These challenges have led to complete crop losses, financial insolvency among hundreds of farmers, and in extreme cases, farmer suicides (Evans/IRII, 2009; Asuming-Brempong and Boakye, 2018). Government-established tomato processing factories remain under-supplied, as local varieties preferred by farmers yield approximately 10 t/ha, with poor fruit quality and low brix (Robinson and Kolavilla, 2010).

Greenhouse cultivation has been shown to produce yields four times higher than those of open-field production (Collins, 2007). The increased field and quality are attributed to improved genetic trials of greenhouse-grown crops and the controlled environment in which they are cultivated. Additionally, pesticide use under greenhouse conditions is generally lower, with higher-quality produce than open-field produce. However, in Ghana, greenhouse technology is underutilized due to limited technical knowledge, resulting in suboptimal management of both structures and crops environmental factors also play a significant role in greenhouse tomato production. High temperatures negatively affect tomato growth and development (Giri *et al.,* 2017; Sang *et al.,* 2016) while fluctuations in relative humidity significantly influence fruit development (Zheng *et al.,* 2020). In temperate regions, humidity control is as crucial as temperature control in tropical regions, both of which directly affect the cost of micro-climate management and, consequently, the overall costs (Katsoulas and Kittas, 2008).

Tomato productivity is closely linked to irrigation management and nutrient supply (Wang *et al.,* 2011; Lanka *et al.,* 2009). Plant nutrient requirements can often be established from water requirements, as both are strongly related to cumulative transpiration patterns during crop development (Báez *et al*., 2003). Nevertheless, the common practice of applying excessive fertiliser to maximize yield often leads to environmental pollution and low fertilizer-use efficiency (Zhu *et al.,* 2012). In Ghana, fertilizer application methods typically include manual broadcasting, side or ring-placement, and foliar spraying. In greenhouses, most farmers adopt drip fertigation but often fail to optimize conditions for water and nutrient uptake, thereby limiting its potential. When managed efficiently, fertigation enhances root activity, improves nutrient mobility and uptake, and reduces the risk of surface and groundwater contamination (Magen, 1995; Elasbah *et al.,* 2019). With increasing water scarcity, especially severe in Northern Ghana during the October to April dry season, there is a need for sustainable irrigation practices. This period of limited water availability reduces farming activity, contributing to seasonal food shortages. Globally, irrigated agriculture accounts for over two-thirds of total freshwater use (Fereres and Soriano, 2007). Strategies such as deficit irrigation have been proposed to conserve water while maintaining economic viability for high-value crops, such as tomato (Abdelhady *et al.,* 2017).

The rising cost of agricultural inputs, including fertilizers, has further constrained production capacity. Sustainable approaches to water and fertilizer management are therefore critical. Despite the importance of integrated water and nutrient management, research on the combined effects of fertilizer rates has been limited. Irrigation regime and its interaction under soilless greenhouse cultivation (Ullah *et al.,* 2021). Potassium (K) is particularly vital, as it plays a major role in plant physiological processes and is essential for tomato production (Lui *et al.,* 2019). Optimal potassium application enhances growth, flowering, yield, and fruit quality, whereas excessive potassium can lead to calcium deficiency disorders such as blossom end rot, reduce yield, and cause economic losses (Patanè and Cosentino, 2010). Potassium application has been shown to influence vegetable biomass significantly, and its interaction with irrigation water strongly affects the characteristics of mature tomato fruit (Saint-Martín-Hernández *et al.,* 2016; Lui *et al.,* 2016). However, little is known about the three-way interaction among fertilizer rate, irrigation regime, and variety under different microclimatic conditions, particularly regarding potassium use efficiency in tomato production.

Materials and Methods

Study Area and Experimental Design

The study was conducted from April 2021 to April 2022 at the Council for Scientific and Industrial Research (CSIR), Savanna Agricultural Research Institute (SARI), Nyankpala, Ghana (N 9°023.321', W 01°000.140). A factorial experiment (3x3x2) consisting of three fertilizer levels (100%: F1, 80%: F2 and 60%: F3), three (3) irrigation water requirement (100%: I1, 80%: I2, 60%: I3) and 2 tomato genotypes (Jalila F1: V1 and Yetty F1:V2) were laid out in a split – split plot design within a greenhouse.

Cultural Practices

Indeterminate tomato genotypes (Jalila F1 and Yetty F1) were raised in a nursery for 21 days and transplanted into a greenhouse. The production was carried out at a crop density of 2.8 plants/meter in a soilless (cocopeat) medium, using a surface drip irrigation system. A tomato fertigation protocol, as disclosed by Peet and Welles (2005), was implemented, with reference to the crop water requirement simulated by CROPWAT 8.0. Calcium nitrate ($CaNO_3$) [15.5 – 0 – 0 + 26.3], Potassium nitrate (KNO_3) [13 – 0 - 46], Mono ammonium phosphate (MAP) [12 – 61 - 0] and Magnesium sulphate ($MgSO_4$) [0 – 0 – 0 – 16 - 32.5] were the soluble fertilizer used. The root zone EC and pH for each treatment were recorded before and after each fertigation throughout the research, adopting the methods described by Awang *et al.* (2009). Each tomato plant was trellised on a single stem, with side shoots pruned. The flowers were pollinated at the flowering stage of the tomato plant, and layering was performed after the plants reached a height of 2 m (Figure 1). Crop cultivation lasted for six months across two microclimates. Thus, micro-climate 1 lasted from April to October 2021, and micro-climate 2 lasted from October 2021 to April 2022.

Climate and Irrigation data

Throughout the experiment, the daily optimal relative humidity and temperature were observed in the greenhouse using data loggers (hydrometer and thermometer, respectively). Fig. 2 had an overall mean temperature and relative humidity of 29.6 oC and 73.7 %, respectively, in micro-climate 1. Fig. 3 had an overall mean temperature and relative humidity of 30.7 °C and 42.9%, respectively, in micro-climate 2. The Optimal temperature for tomato growth, as recommended by Shamshiri *et al.* (2018), is 18.3 to 32.2 ºC and the relative humidity is 50 % to 70 %. Optimal daily temperature and relative humidity, as shown in Figs. 2 and 3, indicate that temperature and relative humidity were occasionally above and below the recommendations of Shamshiri *et al.* (2018). Yang *et al. (*2018) stated that growth is stunted at temperatures above 35 °C.

Fig. 1: Pruning Activities in the Greenhouse

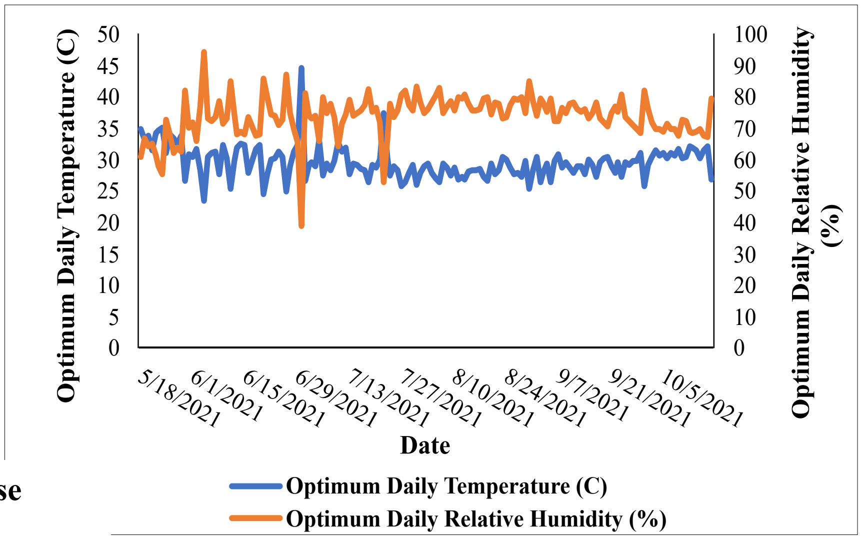

Fig. 2: Optimum Daily Temperature and Relative Humidity in Micro-Climate 1 (April 26th to October 22nd, 2021)

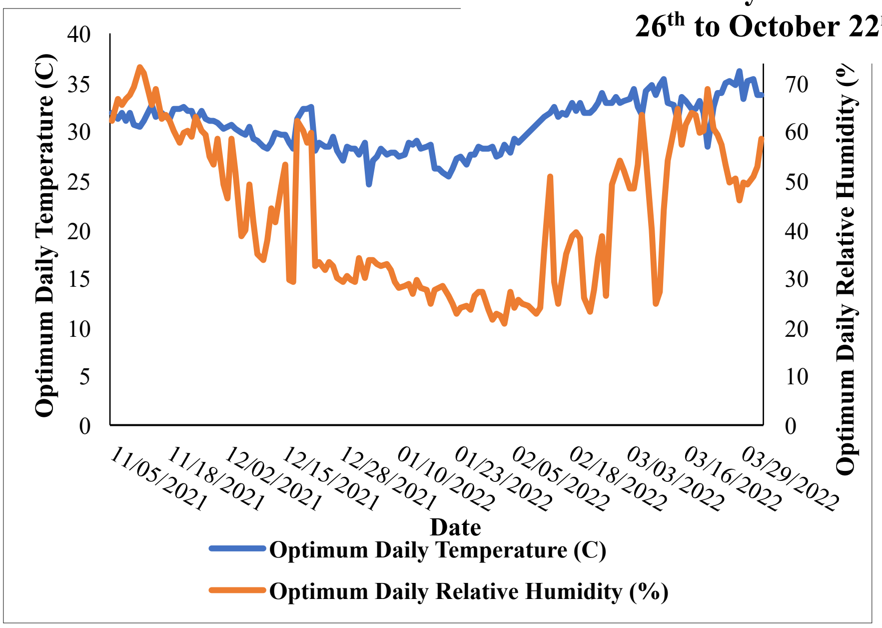

Fig. 3: Optimum Daily Temperature and Relative Humidity in Micro-Climate 2 (October 10th, 2021 to April 8th, 2022)

Climatic records comprising monthly averages of minimum and maximum temperatures, relative humidity, sunshine, wind speed, and geographic coordinates (altitude, latitude, and longitude) were used to estimate reference evapotranspiration (ET) (Allen et al., 1998) with the aid of the CROPWAT 8.0 software. The media (cocopeat) characteristics, including field capacity, permanent wilting point, available water content, and bulk density, were determined using the procedure elaborated by Sujitha and Shanmugasundaram (2017). These parameters were further used to simulate the irrigation schedule using CROPWAT 8.0. Before and after each fertigation, a decagon soil moisture sensor was used to monitor the media moisture content. Equation 1, as indicated by Franco and Maruthi (2022), was used to evaluate the consumptive use and to quantify irrigation.

$$I = A \times Z \times (FC - \theta) \qquad \text{Equation 1}$$

Where; I, is the irrigation quantity (mm); A is the surface area (m^2) of each plot; FC is the Field capacity (m^3/m^3); θ is the volumetric water content before irrigation, and Z is the effective root zone depth (mm).

Agronomist Data

Three plants were randomly selected from each treatment plot across replicates and were tagged for agronomic data collection at 20 weeks after transplanting (WATP). An average plant height and stem girth were measured on each experimental plot, and the average chlorophyll content was recorded using a chlorophyll content meter (Opti-Sciences Model CCM – 200 Plus GPS) on sampled plant leaves, repeated across each replicate. Total yield and potassium use efficiency were recorded based on the total weight of all harvested fruits from sampled plants. Potassium use efficiency was estimated using equation 2 (Singh *et al.,* 2019).

$$KUE = \frac{TY}{TWK} \times 100 \qquad \text{Equation 2}$$

Where KUE is Potassium Use Efficiency (%), TY is the Total Yield (Kg/ha), and TWK is Total Weight of Potassium (Kg/ha).

Leaf, side-shoot, and stem samples were collected to determine fresh and dry weights. Five leaves per replicate were pruned, oven dried at 80 °C for 48 hours, and weighed at 20 WATP. Side-shoots (≤ 20 mm) were counted, weighed fresh, and oven-dried at 80 °C for 24 hours to determine biomass. One stem per replicate was measured for height, weighed fresh, oven-dried at 80 °C for 48 hours, and weighed to obtain stem biomass.

Data Analysis

Fertigation, micro-climate and agronomic data were entered into the Microsoft Excel spreadsheet and statistically analysed. The data were subjected to an analysis of variance (ANOVA) using a split-split plot design model in GenStat Version 12.1. Separation of means was done using the least significant difference at 5% probability. This helped to know the degree of variation among treatment variables. In addition, a correlation matrix and regression model (R^2) were used to understand better the cause-and-effect relationships among fertigation, microclimate, and plant growth variables.

Results and Discussion

Rootzone Electrical Conductivity (EC) and pH as Affected by Fertilizer Level, Irrigation Water Requirement and Variety.

The electrical conductivity of cocopeat was 0.3 dS/m before the experiment. After the experiment, there was no significant variation in rootzone EC due to the interaction among fertiliser level, irrigation water requirement, and variety. Application of treatments increased the rootzone EC while fertilizer level and irrigation water requirement decreased. In micro-climate 1, there was no significant variation in rootzone EC with fertilizer levels, whereas EC varied significantly ($p < 0.05$) with fertilizer levels in micro-climate 2. The variation in rootzone EC after the experiment was highly significant at $p < 0.001$, influenced by irrigation water requirements in micro-climate 1 and 2 (Table 1). Irrigation water requirement of 60% recorded rootzone ECs of 1.84 dS/m and 1.98 dS/m as the highest in micro-climate 1 and 2, respectively. However, the irrigation water requirement at 100% had the lowest rootzone EC of 1.42 dS/m and 1.52 dS/m in micro-climate 1 and 2, respectively. The effect of tomato variety showed no significant variation in rootzone EC across micro-climates 1 and 2. According to Peet and Welles (2005), the rootzone EC threshold for soilless-grown greenhouse tomato is 2.5 dS/m. In this study, the monitored rootzone EC remained within this threshold, supporting the healthy growth of the tomato. However, when the rootzone EC exceeds 2.5 dS/m, the uptake of certain nutrients, such as potassium, calcium, and magnesium, is inhibited (Dorai *et al.,* 2001). This nutrient imbalance leads to deficiency symptoms, including stunted growth and blossom end rot, which can ultimately result in plant death if not corrected.

The rootzone pH of the media (cocopeat) was significantly ($p < 0.01$) affected by the combined effect of fertilizer level, irrigation water requirement and variety in micro-climate 1 and 2. Table 3.1 shows that the interaction of 80 % fertilizer level, 80 % irrigation water requirement, and Yetty F1 gave the lowest rootzone pH of 6.19 and 5.95, respectively, in micro-climate 1 and 2. The highest rootzone pH in micro-climate 1 was 7.35, recorded at the 80% fertilizer level, 60% irrigation water requirement, and Yetty F1. In micro-climate 2, the combination of 60 % fertilizer level, 100% irrigation water requirement, and Jalila F1 recorded the highest rootzone pH of 6.78. An increase in irrigation water requirement decreased rootzone pH in micro-climate 1, whereas in micro-climate 2, rootzone pH increased with increasing irrigation water requirement. Generally, rootzone pH was lower under micro-climate 2 (5.9 – 6.7) than under micro-climate 1 (6.1 – 7.3). Studies by Böhlenius *et al.* (2016) and Putranta *et al.* (2019) emphasized that optimal tomato development occurs within a pH range of approximately 5.0 to 6.0. Deviation from this range may impair the uptake of essential nutrients such as phosphorus, iron and zinc, leading to specific nutrient deficiencies and negatively impacting plant growth. At 20 weeks after transplanting (WATP), pH levels in both microclimates 1 and 2 were mostly near neutrality. There is a strong correlation between plant water uptake and nutrient absorption, as both processes occur through the plant roots. When water uptake is restricted, nutrient uptake is also limited. In dry soils or growing media, the water film between particles shrinks, disrupting mass flow and nutrient diffusion around the roots. The restriction reduces the flow of abscisic acid from roots to leaves, causing stomatal closure and inhibiting photosynthesis as a physiological response to water and nutrient stress (Badr *et al.,* 2018)

Table 1: The Interactive Effect of Fertilizer Level, Irrigation Water Requirement and Genotype on Rootzone pH and Electrical Conductivity in Micro-Climate 1 (April 26th to October 22nd, 2021) and Micro-Climate 2 (October 10th, 2021 to April 8th, 2022)

Treatments	Micro-Climate 1		Micro-Climate 2	
	pH	Electrical Conductivity (dS/m)	pH	Electrical Conductivity (dS/m)
F1I1V1	6.42^{ab}	1.417	6.498^{b}	1.623
F1I1V2	6.745^{bc}	1.432	6.398^{b}	1.467
F1I2V1	7.015^{c}	1.457	6.47^{b}	1.69
F1I2V2	6.987^{c}	1.485	6.369^{b}	1.617
F1I3V1	6.685^{bc}	1.75	6.093^{ab}	1.85
F1I3V2	7.235^{c}	1.962	6.355^{b}	2.055
F2I1V1	6.567^{b}	1.37	6.546^{b}	1.297
F2I1V2	6.565^{ab}	1.355	6.295^{b}	1.359
F2I2V1	6.78^{bc}	1.455	6.365^{b}	1.727
F2I2V2	6.19^{a}	1.615	5.945^{a}	1.783
F2I3V1	6.347^{ab}	1.922	5.986^{ab}	1.865
F2I3V2	7.345^{c}	1.722	6.485^{b}	2.021
F3I1V1	6.692^{bc}	1.352	6.784^{c}	1.535
F3I1V2	6.477^{ab}	1.562	6.551^{b}	1.854
F3I2V1	6.583^{b}	1.61	6.416^{b}	1.857
F3I2V2	6.517^{ab}	1.522	6.409^{b}	1.991
F3I3V1	7.145^{c}	1.825	6.46^{b}	2.058
F3I3V2	7.268^{c}	1.877	6.571^{b}	2.056
Grand Mean	6.754	1.594	6.547	1.761
L.S.D (5 %)	0.3753	0.2706	0.1724	0.2742
F pr.				
F	0.003	0.495	0.032	0.013
I	0.001	<.001	0.052	<.001
V	0.034	0.328	0.539	0.168
F*I	0.073	0.923	0.416	0.105
F*V	0.058	0.584	0.584	0.382
I*V	<.001	0.886	<.001	0.78
F*I*V	0.003	0.113	0.006	0.215

Across the Table, Treatments with Different Letters are Significantly Different at 5 % Probability Level from each Other and vice versa. The Rootzone pH Increase in the Order of a<b<c.

Where: L. S. D: Least Significant Difference; CV: Coefficient of Variation; F.pr: P – value; F: Fertilizer Level; I: Irrigation Water Requirement; and V1: Jalila F1 and V2: Yetty F1.

Plant Height, Stem Girth and Chlorophyll Content as Affected by Crop Fertilizer Level, Water Requirement and Genotype.

The combination of fertilizer, irrigation water requirement, and variety did not statistically influence plant height, stem girth, or chlorophyll content. Plant height exhibited significant variation ($p < 0.05$) influenced by fertilizer levels in micro-climate 2, but not in micro-climate 1 (Table 2). At 20 WATP, the mean plant height recorded was 417 cm and 326 cm, respectively, in micro-climate 1 and 2. Fertilizer level of 100 % recorded the tallest plant height of 444.4 cm and 345.9 cm, respectively, in micro-climate 1 and 2. The shortest plant height was recorded at a fertilizer level of 60% in micro-climate 1 (391 cm) and 2 (289.5 cm). The influence of irrigation water requirement on plant height was highly significant ($p < 0.001$) in micro-climates 1 and 2, as revealed in Table 2. The tallest plant height in micro-climate 1 and 2 was 458.4 cm and 344.4 cm, respectively, and was noted with a 100% irrigation water requirement. A decrease in irrigation water requirement and fertilizer level resulted in reduced plant height. Variety displayed notable variation in plant height. The tallest plant among varieties was Yetty F1, in micro-climate 1 (426.6 cm) and 2 (345.4 cm).

The Stem girth presented from the combined influence of fertilizer level and irrigation water requirement in micro-climate 1 and 2 varied significantly at $p < 0.001$ and $p < 0.05$, respectively, among treatments. In micro-climate 1 and 2, mean stem girths of 8.58 mm and 8.05 mm were recorded, respectively, at 20 WATP. The combination of 100% fertilizer level and 100% irrigation requirement recorded 11.01 mm (micro-climate 1) and 9.83 mm (micro-climate 2) as the maximum stem girth. The interaction of fertilizer level at 60% and irrigation requirement at 80% recorded the thinnest stem girth of 7.47 mm in micro-climate 1. The interaction of fertilizer level of 60 % and 60 % irrigation requirement recorded the thinnest stem girth of 6.66 mm in micro-climate 2. Stem girth decreased with decreasing fertilizer level and irrigation water requirement. Jalila F1 had a thicker stem girth than Yetty F1 in micro-climate 1 and 2.

Chlorophyll content noted from the combined influence of fertilizer level and irrigation water requirement in micro-climate 1 and 2 varied significantly among treatments at $p < 0.05$. In micro-climate 1 and 2, mean chlorophyll content was 60.52% and 39.8%, respectively, at 20 WATP. The combination of 100 % fertilizer level and 100 % irrigation requirement recorded the highest chlorophyll content in greenhouse tomato plants: 75.94 % (micro-climate 1) and 52.03 % (micro-climate 2). The interaction of fertilizer level (60 %) and irrigation requirement (80%) recorded the lowest chlorophyll content of 46.06 % and 32.09 % in micro-climate 1 and 2, respectively. While chlorophyll content in micro-climate 1 statistically varied with the combination of irrigation water requirement and variety, there was no significant variation with this combination under micro-climate 2. Greenhouse tomato variety Jalila F1, when treated with 100 % of the irrigation water requirement, recorded the highest chlorophyll content of 65.65% and 42.94% in microclimates 1 and 2, respectively. In contrast, the lowest chlorophyll content was recorded when the Yetty variety was treated with an irrigation water requirement of 80%, at 55.22 % and 33.50 % in micro-climate 1 and 2, respectively. While Jalila F1 had the highest chlorophyll content, increasing fertilizer levels and irrigation water requirements increased chlorophyll content in greenhouse tomatoes.

Simila, Liu *et al.* (2018) reported that increasing tomato growth and yield depends on the optimal application of water and nutrients. Treatments with no stress during irrigation or fertilizer application showed the highest values for plant height, stem girth, chlorophyll content, side-shoot biomass, leaf biomass, and stem biomass. Comparable findings were also reported by Isah *et al.* (2014), Hou *et al.* (2016), Xiukang and Yingying, (2016), Abdelhady *et al.* (2017), Souri and Dehnavard (2018) and Ullah *et al.* (2021), who all documented significant increases in plant height, stem girth, and leaf area with increased irrigation and fertilizer rates in tomato cultivation. Contrarily, Wankhede *et al.* (2018) observed that plant height was not significantly affected by irrigation regime but was influenced by fertilizer rate. This variation may be attributed to tomato's high nutrient demand, particularly for nitrogen (N), phosphorus (P) and potassium (K) as noted by Hebbar *et al.* (2004). Sack and Scoffoni (2013) explained that leaves carry out photosynthesis to synthesis organic compounds, mainly carbohydrates. Thus, fertilization and irrigation enhance leaf development, thereby increasing the net assimilation of organic nutrients, thereby supporting overall plant development, yield, and quality.

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Table 2: The Interactive Effect of Fertilizer Level, Irrigation Water Requirement and Genotype on Plant Height, Stem Girth and Chlorophyll Content of Greenhouse Tomato in Micro-Climate 1 (April 26th to October 22nd, 2021) and Micro-Climate 2 (October 10th, 2021 to April 8th, 2022).

Treatments	Micro-Climate 1			Micro-Climate 2		
	Plant Height (cm)	Stem Girth (mm)	Chlorophyll Content (%)	Plant Height (cm)	Stem Girth (mm)	Chlorophyll Content (%)
F1I1V1	474.4	11.404	74.4	333.4	9.872	52.18
F1I1V2	476	10.625	77.48	413	9.789	51.88
F1I2V1	415.3	9.833	66.93	305.1	8.71	42.58
F1I2V2	456.2	8.983	57.1	373.3	8.232	34.87
F1I3V1	384.6	8.423	57.22	313.3	8.054	42.91
F1I3V2	460.2	8.608	58.34	337.4	7.157	42.62
F2I1V1	470.1	8.777	63.66	349.1	7.937	41.06
F2I1V2	442.6	7.722	59.54	369.3	7.635	33.13
F2I2V1	379.9	8.324	70.24	354.9	8.858	40.03
F2I2V2	410.1	7.692	65.22	372.5	8.097	36.28
F2I3V1	386.7	8.573	62.77	292.1	7.98	46.19
F2I3V2	403.5	8.302	64.68	318.1	7.339	44.82
F3I1V1	440.6	8.673	58.89	265.5	8.416	35.59
F3I1V2	446.8	8.419	50.63	336.2	7.869	31.64
F3I2V1	348.7	7.541	48.77	296.5	8.412	34.82
F3I2V2	363.5	7.417	43.35	324.9	7.271	29.36

F3I3V1	366.6	7.747	52.67	250.4	6.993	36.01
F3I3V2	380.1	7.509	57.48	263.7	6.342	40.48
Grand Mean	417	8.59	60.52	326.09	8.05	39.8
L.S.D (5 %)	63.05	1.1182	18.211	56.22	0.686	8.659
F pr.						
F	0.079	0.003	0.169	0.042	0.083	0.009
I	<.001	<.001	0.163	< 0.001	< 0.001	0.014
V	0.033	0.011	0.079	< 0.001	< 0.001	0.03
F*I	0.581	0.001	0.031	0.327	0.023	0.009
F*V	0.253	0.539	0.946	0.066	0.97	0.688
I*V	0.117	0.333	0.025	0.07	0.595	0.108
F*I*V	0.663	0.774	0.274	0.316	1.207	0.55

Where: L. S. D: Least Significant Difference; CV: Coefficient of Variation; F.pr: P – value; F: Fertilizer Level; I: Irrigation Water Requirement; V1: Jalila F1 and V2: Yetty F1.

Yield and Potassium Use Efficiency of Greenhouse Tomato as Affected by the Combination of Fertilizer Level, Irrigation Water Requirement and Variety.

Table 3 shows the yield and potassium use efficiency of greenhouse tomato as influenced by the interaction among fertilizer level, irrigation water requirement, and variety. The highest yield in micro-climate 1 was achieved when Jalila F1 was treated with the combination of 100% fertilizer level and 100% irrigation water requirement (101.6 t/ha). In micro-climate 2, Yetty F1, when treated with 100% fertilizer level and 100% irrigation water requirement (91.7 t/ha), recorded the highest yield. The lowest yields were 35.9 t/ha and 25.55 t/ha, recorded when Yetty F1 was treated with the combination of 60 % fertilizer level and 80 % irrigation water requirement in micro-climate 1, and with the combination of 60 % fertilizer level and 60 % irrigation water requirement in micro-climate 2. A significant interaction effect with $p < 0.05$ was observed among fertilizer level, irrigation water requirement, and variety in micro-climate 2. An increase in fertilizer level and irrigation water requirement increased the yield of greenhouse tomatoes. On average, there was a 1.21% difference in total yield across micro-climates, with micro-climate 1 (64.96 t/ha) recording the highest.

The relationships between temperature, relative humidity, and yield in micro-climate 1 and 2 are presented in Equations 3 and 4, respectively.

$$Y_{(\text{Yield})} = 7.679x_{(\text{Optimum Temperature})} + 4.29 \quad R^2 = 0.613,\ p = 0.14 \qquad \text{Equation 3}$$

$$Y_{(\text{Yield})} = 6.125x_{(\text{Optimum Temperature})} + 3. \quad R^2 = 0.502,\ p = 0.24 \qquad \text{Equation 4}$$

The interaction of fertilizer level, irrigation water requirement, and variety did not statistically influence potassium use efficiency of greenhouse tomato in micro-climate 1. Still, it did vary statistically in micro-climate 2. The combination of 100 % fertilizer level and 100 % irrigation water requirement, when applied to Jalila F1 recorded 245.1 % as the highest potassium use efficiency and the least potassium use efficiency (110.4 %) was recorded in Yetty, when treated with the combination of 60 % fertilizer level and 80 % irrigation water requirement in micro-climate 1. However, the combination of 80 % fertilizer level and 80 % irrigation water requirement, when applied to Jalila F1 recorded 120.53 % as the highest potassium use efficiency and the least potassium use efficiency (40.69 %) was recorded in Yetty, when treated with the combination of 60 % fertilizer level and 60

% irrigation water requirement in micro-climate 2. Fertilizer level, irrigation water requirement and variety individually significantly influenced potassium use efficiency.

Abdelhady *et al.* (2017) confirmed that both yield and its components increased with higher irrigation and fertiliser rates, as well as their interaction. These results align with findings by Xiukang and Yingying (2016) and Shabbir *et al.* (2020), who also demonstrated that the combination of fertilizer rates and irrigation regimes significantly influenced tomato yield and fruit biomass. However, Wankhede *et al.* (2018), reported no significant variation in yield due to the interaction of these two factors. Zhu et al. (2017) established that 192 kg/ha is an adequate total potassium application rate. However, increasing potassium beyond this rate reduced the potassium uptake distribution in the fruits, thereby lowering the efficiency of converting potassium fertilizer into yield. This observation is supported by Lui *et al.* (2021), who found that although higher potassium rates, combined with an irrigation deficit, statistically enhanced fruit quality, the overall conversion efficiency decreased with increasing potassium input.

Table 3: The Interactive Effect of Fertilizer Level, Irrigation Water Requirement and Genotype on Yield and Potassium Use Efficiency of Greenhouse Tomato in Micro-Climate 1 (April 26th to October 22nd, 2021) and Micro-Climate 2 (October 10th, 2021 to April 8th, 2022).

Treatments	Micro-Climate 1		Micro-Climate 2	
	Yield (t/ha)	Potassium Use Efficiency (%)	Yield (t/ha)	Potassium Use Efficiency (%)
F1I1V1	101.6	245.1	83.99^{ab}	94.83^{bc}
F1I1V2	94.5	228.1	91.7^{a}	103.54^{ab}
F1I2V1	73.5	177.3	67.54^{bc}	76.26^{c}
F1I2V2	70.2	169.4	77.3^{ab}	87.28^{bc}
F1I3V1	66.5	160.6	55.56^{c}	62.73^{cd}
F1I3V2	61.8	149.1	68.49^{bc}	77.33^{c}
F2I1V1	86.2	245.9	73.83^{b}	116.79^{ab}
F2I1V2	80.4	229.3	72.14^{b}	114.12^{ab}
F2I2V1	79.9	227.9	76.19^{b}	120.53^{a}
F2I2V2	77.5	221.1	75.59^{b}	119.58^{a}
F2I3V1	52.6	150	54.12^{c}	85.61^{bc}
F2I3V2	48	136.9	51.37^{c}	81.25^{bc}
F3I1V1	61.4	188.5	61.73^{bc}	98.31^{b}
F3I1V2	64.6	198.4	70.94^{b}	112.97^{ab}
F3I2V1	37.1	114	53.66^{c}	85.45^{bc}
F3I2V2	35.9	110.4	61.74^{bc}	98.31^{b}
F3I3V1	39.3	120.8	33.65^{d}	53.59^{d}
F3I3V2	38.2	117.4	25.55^{d}	40.69^{d}
Grand Mean	64.95	177.2	64.17	90.51
L.S.D (5 %)	16800.9	46.18	14481.2	19.866

F pr.				
F	<.001	<.001	0.012	0.019
I	<.001	<.001	<.001	<.001
V	0.001	0.002	0.018	0.006
F*I	0.386	0.407	0.004	0.019
F*V	0.788	0.801	0.002	0.015
I*V	0.988	0.99	0.201	0.128
F*I*V	0.994	0.992	0.037	0.035

Across the table, treatments with different letters are significantly different from each other at the 5% probability level, and vice versa. The dry leaf biomass decreases in the order of a>b>c>d. Where: L. S. D: Least Significant Difference; CV: Coefficient of Variation; F.pr: P – value; F: Fertilizer Level; I: Irrigation Water Requirement and V: Variety.

Correlation Between Rootzone Electrical Conductivity (EC) and pH, Micro-Climate Parameters, Growth and Yield of Greenhouse Tomato.

Tables 4 and 5 display the correlations among temperature, relative humidity, rootzone EC and pH, growth parameters, and yield of soilless-grown greenhouse tomato in microclimates 1 and 2, respectively. In micro-climate 1, a strong negative correlation between temperature and relative humidity was observed, whereas in micro-climate 2, a strong positive correlation was observed between temperature and relative humidity. This implies that, in micro-climate 1, a high temperature was accompanied by a low relative humidity, and vice versa. In contrast, in micro-climate 2, a low temperature was accompanied by a low relative humidity. High rootzone pH was associated with high temperatures, while low rootzone pH was associated with low temperatures. In micro-climate 1, yield demonstrated a strong negative correlation with temperature, whereas in micro-climate 2, a weak positive correlation was observed between yield and temperature. In micro-climate 1, plant height and stem girth exhibited a weak negative correlation with temperature, whereas in micro-climate 2, these growth parameters demonstrated a strong positive correlation.

A strong positive correlation was observed between relative humidity and yield in micro-climate 1, whereas a weak negative correlation was observed in micro-climate 2. In micro-climate 1, a positive correlation between relative humidity and stem girth was observed, whereas in micro-climate 2, a high positive correlation (0.655) was noted. Study shows that air temperature and relative humidity influence rootzone pH, development, and yield of greenhouse-grown soilless tomatoes.

Rootzone EC correlated positively with plant height and stem girth. There was a weak correlation of rootzone pH by stem girth in micro-climate 1, but a strong positive correlation of rootzone pH by stem girth in micro-climate 2. Plant showed a weak negative correlation with rootzone pH in micro-climate 1 but a strong positive correlation with rootzone pH in micro-climate 2. This implies that rootzone EC and pH influence the development and yield of greenhouse tomato grown in soilless culture.

Leaf Biomass, Side Shoot Biomass and Stem Biomass of Greenhouse Tomato, as affected by the Combination of Fertilizer Levels, Irrigation Water Requirement and Variety

The influence of the interaction among fertilizer level, irrigation water requirement, and variety on leaf biomass, side-shoot biomass, and stem biomass in micro-climates 1 and 2 is presented in Table 6. Leaf biomass, side-shoot biomass, and stem biomass showed no significant variation in micro-climate 1, as influenced by the combination of fertilizer level, irrigation water requirement, and variety. However, under micro-climate 2, leaf biomass, side-shoot biomass and stem biomass were significantly ($p < 0.001$) influenced by the combination of fertilizer level, irrigation water requirement and variety. The combination of 100% fertilizer level, 60% irrigation water requirement, and Yetty F1 recorded the highest leaf biomass of 2,360 kg/ha in micro-climate 1. Micro-climate 2 revealed that the combination of 100% fertilizer level, 100% irrigation water requirement, and Yetty F1 recorded the highest leaf biomass at 5,023 kg/ha. The combination of 60% fertilizer level, 60% irrigation water requirement, and Jalila F1 recorded the least leaf biomass of 405 kg/ha under micro-climate 1. In micro-climate 2, the combination of 60% fertilizer level, 60% irrigation water requirement, and Yetty F1 recorded the least leaf biomass at 966 kg/ha. The combination of irrigation water requirement and variety significantly affected leaf biomass in micro-climate 1 ($p < 0.05$) and micro-climate 2 ($p < 0.001$).

The combination of 100% fertilizer level and 100% irrigation water requirement, with Jalila F1, recorded the highest side-shoot biomass of 177.9 kg/ha and 157.94 kg/ha in micro-climate 1 and 2, respectively. The combination of 60% fertilizer level, 60% irrigation water requirement, and Yetty F1 yielded 92 kg/ha and 10.43 kg/ha as the lowest side-shoot biomass in micro-climate 1 and 2, respectively. The combination of 100 % fertilizer level, 100 % irrigation water requirement and Jalila F1 recorded the highest stem biomass of 1,368 kg/ha in micro-climate 1. In contrast, in micro-climate 2, 952.3 kg/ha was recorded as the highest stem biomass, achieved with an 80% fertilizer level, 100% irrigation water requirement, and Jalila F1. The combination of a 60% fertiliser level, an 80% irrigation water requirement, and Yetty F1 recorded the lowest stem biomass of 773 kg/ha in micro-climate 1. In contrast, in micro-climate 2, the combination of a 60% fertiliser level, an 80% irrigation water requirement, and Jalila F1 yielded the lowest stem biomass at 423.9 kg/ha. The combination of irrigation water requirement and variety had a highly significant effect on stem biomass ($p < 0.001$). Leaf, stem, and side-shoot biomass increased with increasing fertilization and irrigation water requirements. The Jalila F1 variety recorded the highest leaf biomass and side-shoot biomass. Xiukang and Yingying (2016) found that leaf biomass significantly increased with irrigation and fertilizer application, as well as with their interaction. Similarly, Souri and Dehnavard (2018) reported that fertilizer rate significantly increased side-shoot biomass of greenhouse tomatoes, corroborating the findings of this study. Furthermore, Xiukang and Yingying (2016) indicated that stem biomass varied significantly with irrigation but not with the combined effect of irrigation and fertilizer rate.

Table 4: Correlation between micro-climate parameters, rootzone electrical conductivity and pH, growth and yield of greenhouse tomato in micro-climate 1 (April 26th to October 22nd, 2021).

	Optimum Temperature (°C)	Optimum Relative Humidity (%)	Electrical Conductivity (dS/m)	pH	Yield (t/ha)	Stem Girth (mm)	Plant Height (m)

Optimum Temperature (ºC)	1						
Optimum Relative Humidity (%)	-0.992	1					
Electrical Conductivity (dS/m)	-0.254	0.240	1				
pH	0.369	-0.343	0.246	1			
Yield (t/ha)	-0.718	0.752	0.001	-0.439	1		
Stem Girth (mm)	-0.134	0.079	0.677	0.029	0.156	1	
Plant Height (m)	-0.369	0.313	0.720	-0.035	0.288	0.969	1

Table 5: Correlation between micro-climate parameters, rootzone electrical conductivity and pH, growth and yield of greenhouse tomato in micro-climate 2 (October 10th, 2021 to April 8th, 2022).

	Optimum Temperature (ºC)	Optimum Relative Humidity (%)	Electrical Conductivity (dS/m)	pH	Yield (t/ha)	Stem Girth (mm)	Plant Height (m)
Optimum Temperature (ºC)	1						
Optimum Relative Humidity (%)	0.731	1					
Electrical Conductivity (dS/m)	0.464	0.262	1				
pH	0.753	0.490	0.771	1			
Yield (t/ha)	0.231	-0.337	0.519	0.216	1		
Stem Girth (mm)	0.810	0.655	0.674	0.702	0.423	1	
Plant Height (m)	0.672	0.392	0.699	0.680	0.605	0.947	1

Table 6: The Interactive Effect of Fertilizer Level, Irrigation Water Requirement and Genotype on Leaf Biomass, Side Shoot Biomass and Stem Biomass of Greenhouse Tomato in Micro-Climate 1 (April 26th to October 22nd, 2021) and Micro-Climate 2 (October 10th, 2021 to April 8th, 2022).

Treatments	Micro-Climate 1			Micro-Climate 2		
	Leaf Biomass (Kg/Ha)	Side Shoot Biomass (Kg/Ha)	Stem Biomass (Kg/Ha)	Leaf Biomass (Kg/Ha)	Side Shoot Biomass (Kg/Ha)	Stem Biomass (Kg/Ha)

F1I1V1	2164	177.9	1368	4922[a]	157.94[a]	787.3[bc]
F1I1V2	911	170.6	910	5023[a]	75.57[de]	731.2[bc]
F1I2V1	1536	169.8	894	3245[d]	66.26[e]	615.4[cd]
F1I2V2	1622	101.8	1035	2571[e]	66.03[e]	706.5[c]
F1I3V1	1870	124.4	1006	2177[f]	27.92[g]	741.5[bc]
F1I3V2	2360	132.7	1179	2219[ef]	29.87[g]	621.4[cd]
F2I1V1	2276	122	1255	3985[b]	77.38[d]	952.3[a]
F2I1V2	1606	126.2	932	3055[d]	89.38[c]	827[b]
F2I2V1	1857	131.2	891	2546[e]	126.79[b]	753.8[bc]
F2I2V2	1774	103.3	883	2470[ef]	74.36[de]	788.7[bc]
F2I3V1	846	136.8	1104	4253[b]	35.5[fg]	587[d]
F2I3V2	1375	138.3	940	1905[fg]	30.82[g]	713.6[bc]
F3I1V1	1733	165	1253	3621[c]	77.91[d]	694.1[cd]
F3I1V2	967	114.4	966	2443[ef]	83.62[cd]	685.9[cd]
F3I2V1	1070	118.3	804	2410[ef]	38.55[fg]	423.9[e]
F3I2V2	1399	105.8	773	1588[g]	42.57[f]	734.4[bc]
F3I3V1	405	106.5	909	1927[fg]	33.01[fg]	574.7[de]
F3I3V2	695	92	822	966[h]	10.43[h]	468.1[e]
Grand Mean	1470	129.8	996	2851	63.55	689.3
L.S.D (5 %)	1359.1	57.35	203.6	354.5	9.743	118.71
F pr.						
F	0.292	0.003	0.055	<.001	<.001	0.011
I	0.495	0.16	<.001	<.001	<.001	<.001
V	0.287	0.462	0.101	<.001	<.001	0.07
F*I	0.329	0.059	0.004	<.001	<.001	0.256
F*V	0.803	0.699	0.424	<.001	<.001	0.037
I*V	<.001	0.338	<.001	0.001	0.001	<.001
F*I*V	0.717	0.453	0.236	<.001	<.001	<.001

Across the table, treatments with different letters are significantly different from each other at the 5% probability level, and vice versa. The dry leaf biomass decreases in the order of a>b>c>d>e>f>g>h. Where: L. S. D: Least Significant Difference; CV: Coefficient of Variation; F.pr: P – value; F: Fertilizer Level; I: Irrigation Water Requirement and V: Variety.

Conclusion

This study demonstrated that the combined effects of fertiliser level, irrigation water requirement, and tomato variety substantially affected rootzone EC and pH, plant growth parameters, yield, and biomass accumulation in soilless greenhouse tomato production under different microclimatic conditions. Rootzone EC remained below the 2.5 dS/m threshold, supporting healthy plant development. However, variations in irrigation levels notably affected EC and pH, with micro-climate 2 exhibiting more pronounced responses. Increased irrigation and fertilization generally improved plant height, stem girth, chlorophyll content, and biomass (leaf, stem and side-shoot), particularly when using Jalila F1 and Yetty F1 under optimal water and nutrient supply. Yield and potassium use efficiency were maximised under the combination of 100% fertiliser and 100% irrigation, with notable variations observed across microclimates. Correlation analysis revealed that temperature and relative humidity influenced growth and yield differently in both environments, further highlighting the role of environmental interaction in tomato production. These findings underscore the importance of site-specific management of water and nutrient inputs, alongside appropriate variety selection, to optimise greenhouse tomato productivity and resource-use efficiency in soilless systems.

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Author Contributions

Conceptualization, Y.K. A; methodology, Y.K.A.; software, Y.K.A.; validation, Y.K.A; formal analysis, Y.A.K and I.K.D.; investigation, Y.A.K and I.K.D.; writing original draft preparation, Y.K.A and A.A.; writing, review and editing, A.A.; funding acquisition, A.A, IKD. All authors have read and agreed to the published version of the manuscript.

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