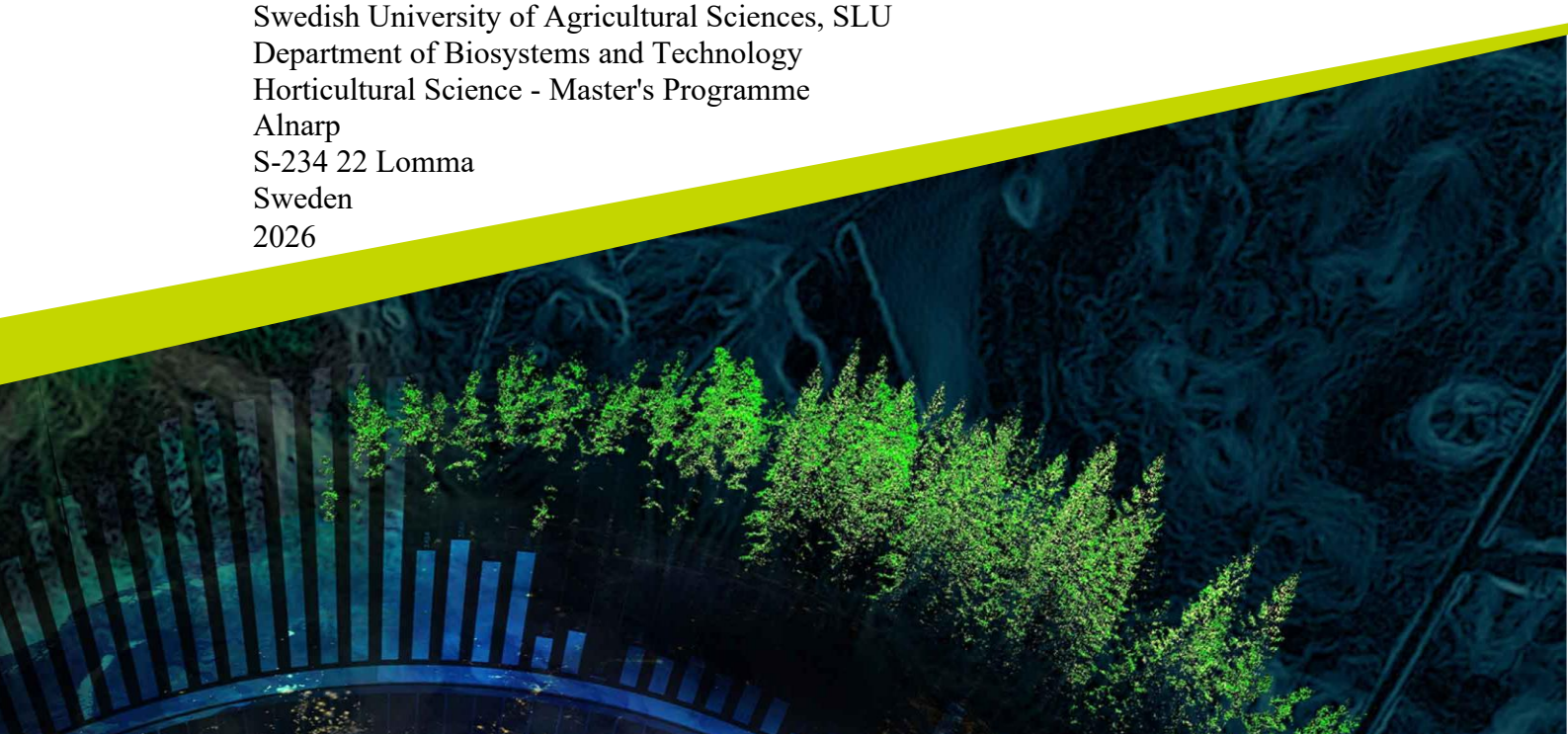
The Impact of Potassium Fertilization on Growth and Quality Parameters of Tomato (*Solanum lycopersicum*) Plants Grown Under Greenhouse Conditions

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Keywords:	Potassium enrichment, tomato, potassium fertilization, fruit quality, total soluble solids (TSS), titratable acidity (TA), TSS/TA ratio, yield, greenhouse production.

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Abstract

Appropriate nutrient availability supports plant growth and enhances both yield and fruit quality in horticulture. In particular, managing potassium (K) levels can influence tomato growth and fruit quality. This study evaluated the effects of potassium enrichment on tomato growth, yield, and fruit quality under greenhouse conditions. Tomato plants were grown in a completely randomized design with three potassium treatments: 100% standard K level (control), enrichment level using 150% K, and enrichment level using 200% K, with seven biological replicates per treatment. Data were analyzed using one-way ANOVA followed by Tukey's HSD test ($p \leq 0.05$) to compare the treatment means. Increasing potassium concentration affected several yield and fruit quality parameters. Fruit yield decreased from 406.64 g plant^{-1} to 374.70 g plant^{-1}, while the number of clusters decreased from 10.6 clusters plant^{-1} under 100% K to 7.3 clusters plant^{-1} under 200% K, respectively. Chlorophyll content measured after harvest increased with potassium enrichment, from 30.48 under 100% K to 40.70 under 200% K. Titratable acidity varied among treatments, with the lowest under 200% K (0.363) and the highest value under 150% K (0.503). Consequently, the total soluble solids to titratable acidity ratio was highest under 200% K (16.71), compared with 13.36 and 12.37 under 100%K and 150% K, respectively. Potassium treatments did not significantly affect plant height, biomass production, fruit number, fruit pH, total soluble solids and chlorophyll content before harvest. Although the total soluble solids to titratable acidity ratio increased under 200% potassium, this change was mainly associated with reduced titratable acidity rather than increase in total soluble solids. These findings indicate that increasing potassium concentration above the 100% potassium levels used in this study did not improve plant growth performance or fruit yield and altered fruit quality through changes in acidity rather than increased sweetness under the tested greenhouse conditions.

***Keywords*: potassium fertilization, tomato, greenhouse conditions, fruit quality, titratable acidity, total soluble solids**

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Abbreviations

Abbreviation	Description
°C	Degree Celsius
No.	Number
ANOVA	Analysis of Variance
Ca	Calcium
CCI	Chlorophyll Content Index
cm	Centimetre (1×10^{-2} m)
EC	Electrical Conductivity
Fe-EDTA	Iron(III)-ethylenediaminetetraacetic acid
g	Gram
HSD	Honestly Significant Difference
K	Potassium
Mg	Magnesium
MHS	Modified Hoagland Solution
SLU	Swedish University of Agricultural Sciences
TA	Titratable Acidity
TSS	Total Soluble Solids
WAT	Weeks After Transplanting
TSS/TA	Total Soluble Solids-to-Titratable Acidity Ratio

1. INTRODUCTION

1.1 Background of Study

Tomato (*Solanum lycopersicum*) is a crucial vegetable crop cultivated worldwide for its nutritional value, economic significance, and diverse applications in both fresh consumption and processing. It ranks second among vegetables in terms of production and consumption (Amr & Raie, 2022). The crop plays an important role in worldwide horticultural production because it provides several important nutrients and bioactive compounds, including lycopene, β-carotene, vitamin C, and flavonoids (Gerszberg et al., 2015). Quinet et al. (2019) explained tomatoes as a major horticultural crop with complex fruit development processes, including physiological, agricultural, biochemical, and metabolic changes that determine final fruit properties. Kaymak and Aksoy (2025) reported that tomato production has significant economic importance in European agriculture, where both productivity and fruit quality contribute to market value.

In modern tomato production, achieving a high yield alone is no longer the main production goal. Fruit quality is a critical factor because consumer acceptance depends strongly on sensory characteristics, nutritional value, and visual appearance. Farneti (2014) explained that tomato quality is influenced by the interaction among genotype, cultivation practices, and post-harvest conditions, which together determine the final characteristics experienced by consumers. As reported by Gatahi (2020), tomato production faces several challenges, including high input costs, pest and disease pressure, post-harvest losses, and the need for efficient resource management. Tomato fruit quality is determined by its physical, chemical, nutritional, and sensory attributes. Fruit size, color, firmness, and shape are important factors, whereas sweetness, acidity, aroma, and nutritional composition contribute to consumption quality and consumer acceptance (Villanueva Gutierrez, 2018; Amr and Raie, 2022; Portugal et al., 2015). Among the chemical attributes, soluble solids and organic acids are important determinants of flavor. Sierra Cadavid (2014) reported that glucose and fructose are major contributors to soluble solids, which vary with cultivars and ripening stages, while Jones Jr. (2007) reported soluble solids values of approximately 4.5- 7.0% among tomato cultivars. Tieman et al. (2017) showed that tomato flavor perception depends on the balance among sugars, organic acids, and volatile compounds. The volatile compounds also contribute substantially to tomato aroma. Baldwin et al. (2000) also reported that these components contribute to the overall sensory quality of tomato. Furthermore, Moneruzzaman et al. (2008) revealed that maturity and ripening conditions influence soluble solids and acidity of fruits. Jones Jr. (2007) further reported the effect of lycopene and β-carotene on tomato colour. Wilkerson et al. (2013) also identified soluble solids as an important quality indicator,

particularly for processing tomatoes. According to Abegaz et al. (2004), higher soluble sugar levels in tomato fruits are normally associated with higher sweetness and consumer acceptance.

1.2 Role of Nutrient Management in Tomato Quality Optimization

Plant nutrition is one of the most important factors influencing tomato growth, fruit development, and quality by regulating photosynthesis, enzyme activity, carbohydrate production, and fruit maturation. Ranasinghe and Weerakkody (2006) investigated the effects of fertilizer dosage and nutrient balance on greenhouse tomatoes and reported that appropriate nutrient management is necessary to achieve optimal plant growth and nutrient uptake.

In greenhouse production systems, nutrient management is particularly important because plants depend mainly on externally supplied nutrient solutions. Kaur et al. (2016) studied the use of MHS for greenhouse tomato production and demonstrated that maintaining a balanced nutrient supply is essential for supporting healthy plant growth under controlled conditions. Maharaja and Singh (2006) investigated the influence of irrigation and fertigation management on greenhouse tomato production. This study showed that nutrient and water management practices affect plant growth, yield formation, and fruit characteristics. This demonstrates that fertilizer management should not only focus on increasing biomass production but also on improving fruit quality parameters that are important for market acceptance. Nutrient balance is especially important because excessive application of one nutrient can interfere with the uptake and functions of other essential elements. Van Delden et al. (2020) emphasized that the composition of nutrient solutions influences plant performance in controlled cultivation systems, demonstrating the importance of maintaining appropriate nutrient ratios rather than increasing individual nutrients without considering the overall balance.

1.3 Role of Potassium in Tomato Fruit Quality

Potassium (K) is one of the most important macronutrients that influences tomato fruit development and quality. Unlike nitrogen and phosphorus, potassium does not form a structural component of plants but acts as a major regulator of physiological and biochemical processes in plants. Cakmak (2005) explained that potassium contributes to enzyme activation, photosynthetic regulation, osmotic adjustment, and stress tolerance mechanisms in plants. Potassium plays a particularly important role in tomato fruit quality because it regulates the movement of carbohydrates from the leaves to the developing fruits. Javaria et al. (2012) investigated the effect of potassium application on the chemical and sensory attributes of tomato fruits and reported that potassium improved fruit quality

characteristics by enhancing sugar accumulation and improving sensory properties. Their findings indicate that K availability directly affects flavour development and consumer acceptance. The relationship between potassium and fruit quality has also been studied in greenhouse tomato cultivation. Çolpan et al. (2013) studied the effect of potassium application on tomato yield and fruit quality components and reported that potassium applications with different K, Ca, and Mg ratios improved characteristics such as soluble solids content and overall fruit quality. These findings suggest that appropriate K fertilization can enhance both productivity and market value.

Potassium also influences plant physiological performance under stressful conditions. Shabani et al. (2012) evaluated K and Ca levels in salinity-stressed cherry tomato plants and found that K availability affected vegetative growth and nutrient uptake under stress conditions. This indicates that K contributes not only to fruit quality development but also to maintaining plant physiological stability.

However, potassium application must be carefully managed because excessive potassium levels may disturb the nutrient balance. Bar-Tal and Pressman (1996) reported that K^+ concentration affects cations and physiological disorders in greenhouse tomatoes. Their findings showed that high potassium availability can influence calcium uptake and increase the risk of nutrient-related quality problems. Therefore, determining an appropriate K concentration is essential for achieving optimal fruit quality without causing nutrient imbalance.

1.4 Importance of Potassium Optimization for Horticultural Production

Sustainable horticultural production requires management strategies that improve crop quality while maintaining the efficient use of resources. Greenhouse tomato production systems provide opportunities for precise nutrient management; however, successful production depends on identifying nutrient levels that support both plant performance and consumer-oriented quality traits. Naseer et al. (2021) evaluated the environmental impacts of different tomato production strategies and emphasized the importance of improving resource efficiency in greenhouse production systems. Efficient fertilizer management can reduce unnecessary nutrient loss while maintaining productivity. Therefore, optimizing potassium application is an important approach in modern horticulture because potassium influences fruit sweetness, flavor balance, physiological performance, and overall market value. Timileyin et al. (2025) reported that potassium fertilizer rate affected tomato growth, yield, and nutritional quality, highlighting the importance of selecting appropriate potassium levels for different production systems.

Previous studies have demonstrated the importance of K in tomato production. Many investigations have examined potassium together with other factors, such as salinity, irrigation, or general fertilizer management. Limited

information is available regarding the specific effect of potassium enrichment under controlled nutrient conditions on quality parameters, such as TSS, TA, and TSS/TA ratio. Therefore, further research is required to determine how potassium enrichment influences tomato quality while maintaining balanced plant growth. Tomato fruit quality is influenced by several interacting factors, including cultivar characteristics, environmental conditions, cultivation practices, and nutrient availability. Previous studies have clearly demonstrated that mineral nutrition, particularly potassium, plays an important role in regulating fruit quality parameters such as soluble solids content, acidity, and flavor characteristics. However, most previous investigations have evaluated the effects of potassium together with other production factors, including irrigation management, salinity stress, and general fertilizer application.

For example, Mahajan and Singh (2006) investigated the combined effects of irrigation and fertigation management on greenhouse tomato production, demonstrating the importance of nutrient supply management for plant performance. Shabani et al. (2012) evaluated the effects of K under salinity stress conditions and reported that K influences plant growth and nutrient uptake in stressful environments. Although these studies provide valuable information, they do not fully explain the specific response of tomato fruit quality to potassium enrichment under controlled nutrient conditions.

Similarly, previous studies by Javaria et al. (2012) and Çolpan et al. (2013) demonstrated that K application can improve the chemical and sensory quality characteristics of tomatoes. However, the optimal potassium concentration required to improve flavour-related parameters while maintaining balanced plant growth remains unclear, particularly in greenhouse cultivation systems using controlled nutrient conditions. Therefore, further research is needed to understand how different K levels independently influence tomato growth, fruit quality, and nutrient balance. This information is important for developing efficient K management strategies that support high-quality tomato production in modern horticultural systems.

1.5 Research Gap

Previous studies have often investigated potassium together with other factors such as irrigation management, soil type, nutritional interaction, or combined fertilizer treatments (Bar-Tal & Pressman, 1996; Çolpan et al., 2013). These interacting factors make it difficult to determine the specific contribution of potassium fertilization to plant growth and fruit quality. Furthermore, much of the available research has focused primarily on increasing yield, whereas comparatively fewer studies have evaluated how different potassium fertilization levels influence flavor-related quality attributes, including TSS, TA, pH, and the TSS/TA ratio under controlled nutrient conditions. In addition, the potassium

fertilization that provides an appropriate balance between vegetative growth, reproductive development, fruit yield, and fruit quality has not been clearly established. This knowledge is important for developing fertilization strategies that improve nutrient efficiency while producing tomatoes with high market value and consumer acceptance. This research is required to evaluate the effect of potassium fertilization under a controlled nutritional regime in which other essential nutrients are maintained at similar concentrations.

1.6 Problem Statement

Modern horticultural production aims to produce tomatoes that combine high productivity and superior fruit quality while maintaining low production costs and environmental impact. Fertilizer management is one of the most important factors influencing these objectives because nutrient availability directly affects plant growth, fruit development, and quality. Although potassium fertilization has been widely recognized as an important factor affecting tomato quality, uncertainty remains regarding the potassium level required to maximize fruit quality without causing nutrient imbalances or unnecessary fertilizer application to the soil. Excessive potassium application may interfere with the uptake of Ca and Mg, reducing nutrient-use efficiency and potentially affecting plant performance and fruit quality (Bar-Tal & Pressman, 1996). Conversely, insufficient potassium supply can limit carbohydrate transport, reduce sugar accumulation, and negatively affect flavor development (Cakmak, 2005). Consequently, growers often lack clear evidence-based recommendations regarding potassium fertilization strategies that simultaneously improve growth, yield, and fruit quality. Addressing this problem requires studies that evaluate the specific effects of potassium fertilization while maintaining other nutrients at constant levels. Such information is crucial for management strategies aimed at enhancing tomato production and fruit quality in horticulture.

1.7 Justification of the Study

Optimizing potassium fertilization is becoming increasingly important in horticulture because consumers demand tomatoes with improved sweetness, balanced acidity, desirable flavor, and high nutritional value. Simultaneously, growers must use fertilizers efficiently to reduce production costs, improve nutrient-use efficiency, and minimize the environmental impacts associated with excessive fertilizer application. Therefore, identifying appropriate potassium fertilization strategies is important for sustainable tomato production.

This study contributes to horticultural science by providing information on how different potassium fertilization levels influence vegetative growth, reproductive development, fruit yield, and important quality parameters, including total soluble solids (TSS), titratable acidity (TA), pH, and TSS/TA ratio. By

evaluating potassium under controlled nutrient conditions, this study provides a clearer understanding of the effect of potassium enrichment on tomato performance.

These findings are expected to support the development of evidence-based fertilization recommendations that improve fruit quality while maintaining efficient nutrient management. This research will also contribute to sustainable horticultural production by promoting fertilizer-use practices that enhance crop quality, increase resource-use efficiency, and reduce unnecessary fertilizer inputs.

1.8 Overall goal

The overall goal of this study was to evaluate the effects of different potassium concentrations on tomato growth, yield and fruit quality under greenhouse conditions. The study aims to provide information to support appropriate potassium management strategies for sustainable greenhouse tomato production.

1.9 Objectives of the Study

The objectives of this study were,

- To evaluate the effects of different potassium fertilization levels on the vegetative and reproductive growth of tomato plants.
- To evaluate the influence of potassium fertilization on tomato fruit yield.
- To evaluate the impact of varying potassium fertilization levels on fruit quality parameters, total soluble solids, titratable acidity, pH, and the total soluble solids-to-titratable acidity ratio.
- To determine the potassium fertilization level that optimally balances plant growth, yield, and fruit quality, thereby supporting efficient nutrient management in horticultural tomato production.

1.10 Research questions

This study aims to answer the following research questions:

- How do different potassium levels influence tomato plant growth, development, and fruit quality characteristics?
- Which potassium level provides the most suitable balance between tomato, total soluble solids and titratable acidity ratio?
- What potassium concentration optimally balances tomato yield and fruit quality?

1.11 Hypotheses

1.11.1 Null hypothesis (H_0)

Different potassium fertilization levels do not significantly affect vegetative growth, reproductive development, fruit yield, and fruit quality parameters, including total soluble solids, titratable acidity, pH, and the total soluble solids-to-titratable acidity ratio under control nutrition conditions.

1.11.2 Alternative hypothesis (H_1)

Different potassium fertilization levels significantly influence vegetative growth, reproductive development, fruit yield, and fruit quality parameters, including total soluble solids, titratable acidity, pH, and the total soluble solids-to-titratable acidity ratio under control nutrition conditions. Potassium enrichment is expected to improve fruit quality by enhancing sweetness and flavor balance while maintaining satisfactory plant growth and yield.

2. MATERIALS AND METHODS

2.1 Location

The experiment was conducted in a greenhouse chamber at the Department of Biosystems and Technology, Swedish University of Agricultural Sciences (SLU), Alnarp, Sweden. The greenhouse was equipped with an automated environmental control system, in which ventilation and temperature were regulated automatically throughout the experimental period, and fertilizer application and watering were performed manually. The temperature was maintained at approximately 18–26 °C, with the ventilation setpoint adjusted from 22 °C to 20 °C during the experiment. The relative humidity ranged between 25% and 100%. The two artificial lamps (400W SON-T high-pressure sodium lamps) were turned on daily at 06h00 and turned off at 22h00 to provide lighting.

2.2 Materials

The tomato cultivar used in this experiment was the Sweet Sturdy F1 Jo tomato cultivar. Tomato plants were cultivated in plastic pots with a total volume of 2 L each. The cultivar is a compact, micro-dwarf, pot-grown cherry tomato; therefore, plants were grown without pruning or specific training. Pollination occurred naturally during the experiment (Semenco. (n.d.). The growing substrate was pumice. Pumice has a relatively low nutrient retention capacity. Therefore, crop performance depends strongly on the supply of nutrient solution and accurate nutrition management (Papadopoulos, 2008). MHS was used as the base. Potassium treatments were established by supplementing the nutrient solution with potassium sulfate (K_2SO_4) to achieve different potassium levels.

2.3 Experimental design

The experiment was conducted using a completely randomized design with three treatments and seven biological replicates per treatment, resulting in 21 tomato plants. At the beginning of the experiment, the pots were randomly assigned to their positions and then remained in the same positions throughout the experimental period. Sweet Sturdy F1 Jo tomato cultivar was selected due to its stable vegetative growth, consistent yield, and reliable fruit quality in greenhouse cultivation. MHS was used as the nutrient source for all treatments and as the control (T1). Treatment T1 received the standard potassium concentration of the nutrient solution (100% K, approximately 273 mg L^{-1} K). Potassium enrichment treatments were prepared by adding potassium sulphate to the working solutions to increase the potassium concentration to 150% K (T2) and 200% K (T3) relative to the control. The additional K_2SO_4 applied for T2 and T3 was 0.33 g L^{-1} and 0.61 g L^{-1}, respectively.

Because K_2SO_4 contains both potassium and sulphate, the observed effects cannot be attributed exclusively to potassium enrichment. The EC of the working nutrient solution before potassium enrichment was approximately 1.9-2.0 dS m^{-1} for T1. After adding K_2SO_4, the EC of the potassium-enriched treatment increased to approximately 2.3-2.4 dS m^{-1} for T2 and 2.6-2.7 dS m^{-1} for T3, respectively. During the early vegetative stage, distilled water was added to all treatment solutions to adjust the EC to 1.5-1.6 dS m^{-1} before application. After the early vegetative stage, no further dilution was performed to maintain the intended K enrichment levels.

2.4 Preparation of Modified Hoagland Solution

Modified Hoagland solution was used for tomato cultivation in a pumice-based substrate. The nutrient solution was prepared according to the formulation described by Kaur et al. (2016). Separate stock solutions of macronutrients and micronutrients were prepared using analytical-grade chemicals and distilled water (Table 1). For each fertilizer application, the working nutrient solution was prepared by diluting the required volume of stock solutions with distilled water according to the formulation of Kaur et al. (2016) (Table 2). The standard MHS used for the control treatment contained calcium nitrate tetrahydrate, potassium nitrate, monopotassium phosphate, magnesium sulfate heptahydrate, micronutrients, and Fe-EDTA. The composition of the stock solutions and the volumes used to prepare the working nutrient solutions are presented in Tables 1 and 2, respectively.

Table 1. Preparation of 1 L Stock Solutions for the Modified Hoagland Solution.

Stock solution	Component	Amount (g L^{-1})
Calcium nitrate tetrahydrate	$Ca(NO_3)_2 \cdot 4H_2O$	236
Potassium nitrate	KNO_3	101.1
Monopotassium phosphate	KH_2PO_4	136.1
Magnesium sulphate heptahydrate	$MgSO_4 \cdot 7H_2O$	246.5
Micronutrient solution	H_3BO_3, $MnCl_2 \cdot 4H_2O$, $ZnSO_4 \cdot 7H_2O$, $CuSO_4 \cdot 5H_2O$, $Na_2MoO_4 \cdot 2H_2O$	See preparation below*
Fe-EDTA solution	EDTA·2Na, $FeSO_4 \cdot 7H_2O$, KOH	See preparation below*

**Micronutrient and Fe-EDTA stock solutions were prepared separately according to the modified Hoagland solution as below.*

The micronutrient and iron stock solutions were prepared separately using distilled water. For the micronutrient stock solution, 2.8 g of boric acid (H_3BO_3), 1.8 g of manganese chloride tetrahydrate ($MnCl_2 \cdot 4H_2O$), 0.2 g of zinc sulphate heptahydrate ($ZnSO_4 \cdot 7H_2O$), 0.1 g of copper sulphate pentahydrate ($CuSO_4 \cdot 5H_2O$), and 0.025 g of sodium molybdate dihydrate ($Na_2MoO_4 \cdot 2H_2O$) were dissolved in distilled water, then made up to a final volume of 1 L. The iron chelate (Fe-EDTA) stock solution was prepared by dissolving 10.4 g of disodium EDTA (EDTA.2Na),7.8 g of iron sulphate heptahydrate ($FeSO_4 \cdot 7H_2O$), and 56.1 g of potassium hydroxide(KOH) in distilled water, followed by adjustment to a final volume of 1 L (Kaur et al., 2016).

Table 2. Composition of the working nutrient solution (per litre). The working nutrient solution was freshly prepared for the control treatment (T1; 100% K) according to the modified Hoagland solution described by Kaur et al. (2016). Additional K_2SO_4 was added to the working nutrient solution to achieve the respective potassium-enrichment levels. K_2SO_4 contains approximately 44.9%K and 55.1% SO_4^{2-} by weight. Therefore,0.33 and 0.61 g L^{-1} supplied approximately 148 and 274 mg L^{-1} K and 182 and 336 mg L^{-1} SO_4^{2-} respectively.

Stock solution	Component	T1: 100% K (Control)	T2: 150% K	T3: 200% K
Calcium nitrate tetrahydrate (mL L^{-1})	$Ca(NO_3)_2 \cdot 4H_2O$	7	7	7
Potassium nitrate (mL L^{-1})	KNO_3	5	5	5
Monopotassium phosphate (mL L^{-1})	KH_2PO_4	2	2	2
Magnesium sulphate heptahydrate (mL L^{-1})	$MgSO_4 \cdot 7H_2O$	1	1	1
Micronutrient solution (mL L^{-1})	H_3BO_3, $MnCl_2 \cdot 4H_2O$, $ZnSO_4 \cdot 7H_2O$, $CuSO_4 \cdot 5H_2O$, $Na_2MoO_4 \cdot 2H_2O$	1	1	1
Fe-EDTA solution (mL L^{-1})	EDTA·2Na, $FeSO_4 \cdot 7H_2O$, KOH	1	1	1
Additional Potassium sulphate (g L^{-1})	K_2SO_4	-	0.33	0.61

2.5 Irrigation and Fertigation

Fertilizer was applied twice a week, beginning 18 days after transplanting. Each plant received 250 mL of the respective working nutrient solution at each application. Irrigation was provided manually according to the crop growth stage, substrate moisture, greenhouse temperature, and evapotranspiration demand. Plants were irrigated daily or every other day with water only. Trays were placed directly beneath the pots to collect drainage. The trays were closely fitted to the bottom of the pots, allowing the drainage solution to remain in contact with the roots. As a result, the nutrient solution collected in the trays helped prevent nutrient loss through drainage and leakage, and also remained available for root uptake, while reducing direct exposure to the air. On fertigation days, water was supplied first, and the water collected in trays was removed before fertigation. Nutrient solution was applied approximately three hours later. Before each fertiliser application, the pH and EC of the working nutrient solution were measured using a Hanna Instruments HI-98129 combo pH/EC/TDS tester. It measures pH, EC, and temperature simultaneously. The pH was maintained between 5.8 and 6.5. Electrical conductivity (EC) was monitored as an indicator of the nutrient concentration of the solution, as EC is closely related to nutrient availability and influences plant growth and nutrient uptake (Samarakoon et al., 2006). Throughout the experiment, EC and pH adjustments were monitored before application, as described above. After completion of the early vegetative stage of the plant, a nutrient solution was applied without further dilution to maintain the established K enrichment treatments.

2.6 Data Collection and Analysis

Plant growth and development, biomass production, and fruit quality parameters were evaluated during the experiment. Data were collected from all 21 plants, with seven biological replicates per treatment. The responses of the control treatment (T1:100% K) and potassium enrichment treatments (T2:150 % K, T3:200 % K) were compared to determine the effect of increasing potassium concentration on tomato growth, performance, and fruit quality under greenhouse conditions.

2.6.1 Plant Growth Analysis

Vegetative and reproductive growth parameters were recorded from the 6th week after transplanting (WAT), periodically at two-week intervals. Vegetative growth characteristics included plant height and the number of leaves per plant. After initiation of flowering, reproductive parameters were evaluated by recording the numbers of flowers, fruits, and clusters.

Measurements were taken from fully expanded mature leaves, and each plant was measured in triplicate. Chlorophyll measurements were obtained before and after harvest. Chlorophyll content was measured at two growth stages before harvest (9 WAT) and after the final harvest (15 WAT) using an MC-100 Chlorophyll Content Meter (Apogee Instruments, USA), and the chlorophyll content was expressed as Chlorophyll Content Index (CCI). According to Jiang et al. (2017), chlorophyll is a major photosynthetic pigment and is useful in light capture and photosynthetic activity. The chlorophyll concentration affects the physiological condition of plants. As reported by Al-Gaadi et al. (2024), reduced chlorophyll content may be influenced by lower photosynthetic activity and productivity. Adequate potassium nutrition may help maintain plant physiological activity during reproductive development. Measurements were taken from fully expanded healthy leaves, and the average chlorophyll content value was calculated for each plant.

Plant biomass production was determined after the final harvest of the plants. Plants were separated into leaves, stems, and roots, and the fresh weights of each component were recorded. Plant samples were subsequently dried at a constant temperature for 72 hours until a constant dry weight was achieved. The dry weights of individual plant components were recorded, and the total dry biomass was calculated as the sum of the leaf, stem, and root dry weights. The mean biomass per plant was calculated for each K treatment.

2.6.2 Fruit Quality Analysis

Fruit quality analysis was performed using fully ripened red tomato fruits collected from each treatment group at harvest. Quality parameters were evaluated to determine the effect of potassium enrichment on fruit sweetness, acidity, and flavor characteristics. For TSS measurements, three fruits were selected, while for TA and pH measurements, six to eight fruits were selected per plant from different clusters. Total soluble solids (TSS) were measured using a Hanna Instruments HI 96801 digital refractometer and expressed as ^{o}Brix. The °Brix is an indicator of the soluble sugar content and sweetness of tomato fruits. Fully red ripe fruits were selected and used from each plant based on visual assessment of uniform colour and comparable fruit size. The reflectometer was first calibrated to 0.0 °Brix using 2-3 drops of distilled water according to the manufacturer's instructions. Then the prism surface was gently dried using soft tissue paper. After calibration, 2-3 drops of filtered tomato juice were then placed on the prism, and the °Brix reading displayed on the digital screen was recorded. The mean °Brix value was calculated from three measurements obtained from each replicate. The tomatoes were stored at -20 ^{o}C until further analysis.

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The pH of the tomato juice was measured using a digital pH meter (Hanna Instruments HI-98129 combo pH/EC/TDS tester). The pH meter was calibrated using standard buffer solutions before measurements (Teka, 2013). 40 mL sample of tomato juice was transferred into a clean 100 mL beaker, and after measuring the pH of each sample, the electrode was rinsed with distilled water and gently dried before measuring the next sample to prevent cross contamination. Titratable acidity was determined using an acid-based titration method. Frozen fully ripe tomato fruits stored at -20 °C were brought to room temperature before analysis. Each tomato was thoroughly blended and pulp was filtered to obtain a homogeneous juice sample. Then 10 mL of the filtered juice sample was diluted to 50 mL with distilled water. The diluted sample was titrated with 0.1N sodium hydroxide (NaOH) solution. A digital pH meter was used to monitor the titration, and the endpoint was determined at pH 8.1, which corresponds to the equivalence point for citric acid (Sapers et al., 1977). Titratable acidity was expressed as a percentage of citric acid equivalent and calculated using the following formula (Paul et al., 2010). For each replicate, three titrations were done to determine titratable acidity. The mean of the three measurements was used to calculate the treatment mean.

$$\text{Titratable acidity } \mathbf{(\%)} = \frac{V \times N \times E \times 100}{Vs \times 1000}$$

V = volume of NaOH consumed (mL)
N = Normality of NaOH (0.1N)
E = The equivalent weight of citric acid (64.04)
Vs = Vs is the volume of the sample evaluated (mL).

2.7 Data processing and statistical analysis

All collected experimental data were initially organized and processed using Microsoft Excel and Minitab (version 22). The treatment means and standard errors were calculated. Graphical representations and tables were prepared to illustrate the differences among the potassium treatments in terms of growth, biomass, chlorophyll, and fruit quality parameters. A one-way analysis of variance (ANOVA) was performed to determine the effects of K enrichment treatment on plant growth, yield, chlorophyll content, and fruit quality parameters. When significant differences were detected, pairwise comparisons (Tukey's HSD test) were performed using a test at a 5% significance level ($p \leq 0.05$) (Nanda et al., 2021).



(a) (b)

Figure 1. Tomato plants during the fruiting and harvesting stage: (a) the 21 experimental plants in the greenhouse and (b) a representative plant with fully red-ripe fruits.

3. RESULTS

3.1 Effect of Potassium Enrichment on Vegetative Growth Parameters

The effect of potassium enrichment on the vegetative growth parameters of tomato plants during the cultivation period is presented in Table 3. During the early vegetative growth stage (6 and 7 weeks after transplanting), potassium treatments did not significantly affect the number of leaves (6 WAT, p = 0.387; 7 WAT p= 0.387) or plant height (6 WAT, p = 0.291; 7 WAT, p= 0.364). However, at 9 WAT, the number of leaves was significantly influenced by the potassium treatments ($p < 0.001$). The T1 (control) and moderate potassium treatment T2 (150% K)resulted in a higher number of leaves than the highest potassium treatment (T3). However, plant height was unaffected by K application (p = 0.204). At 11 weeks, the number of leaves continued to show significant differences among the treatments (p = 0.014), with T1 (control) showing the highest value, followed by T2 (150% K) and T3 (200% K) . In contrast, no significant differences were observed in plant height during the experimental period ($p > 0.05$).

*Table 3. Effect of potassium treatments on vegetative growth parameters of tomato plants at different weeks after transplanting. Values are presented as mean ± standard error (SE) (n = 7). Different superscript letters within the same column indicate significant differences among treatments according to Tukey's HSD test at p ≤ 0.05. NS = not significant; * = significant at p ≤ 0.05; *** = significant at p ≤ 0.001.*

Week After Transplanting (WAT)	Treatment	No. of leaves	Height (cm)
6	T1(control)	5.3 ± 0.2	5.81 ± 0.2
	T2(150%K)	5.0 ± 0.2	5.57 ± 0.3
	T3(200%K)	5.0 ± 0.3	6.10 ± 0.3
	p value	0.387 NS	0.291NS
7	T1(control)	7.1 ± 0.3	7.47 ± 0.4
	T2(150%K)	6.7 ± 0.2	6.85 ± 0.3
	T3(200%K)	6.7 ± 0.3	7.20 ± 0.30
	p value	0.387NS	0.364NS
9	T1(control)	9.7 ± 0.7[a]	10.62 ± 0.5
	T2(150%K)	9.0 ± 0.4[a]	11.6 ± 0.5
	T3(200%K)	6.7 ± 0.3[b]	11.5 ± 0.2
	p value	<0.001***	0.204NS
11	T1(control)	12.6 ± 0.8[a]	14.25 ± 0.8

	T2(150%K)	10.7 ± 0.2[ab]	13.8 ± 0.3
	T3(200%K)	10.7 ± 0.3[b]	13.4 ± 0.4
	p-value	0.014*	0.559NS
13	T1(control)	15.3 ± 0.8	16.6 ± 0.7
	T2(150%K)	13.7 ± 0.6	16.1 ± 0.8
	T3(200%K)	14.6 ± 1.2	16.2 ± 0.5
	p value	0.482NS	0.866NS
15	T1(control)	17.5 ± 2.8	17.0 ± 2.3
	T2(150%K)	15.9 ± 1.9	16.8 ± 2.2
	T3(200%K)	16.6 ± 3.5	17.1 ± 1.4
	p value	0.531NS	0.961NS

3.2 Effect of Potassium Enrichment on Reproductive Growth Parameters

The effects of K treatment on the reproductive parameters of tomato plants at different weeks after transplantation are shown in Table 4. At 7 WAT, the number of clusters and flowers did not differ significantly among the treatments ($p = 0.260$ and $p = 0.327$, respectively). At 9 WAT, flower production differed significantly among the treatments ($p = 0.041$), with T1 (control) producing the highest number of flowers followed by T2 (150% K) and T3 (200% K). At 9 WAT, the number of clusters showed a decreasing trend with increasing potassium levels from 5.4 ± 0.5 in T1(control) to 5.1 ± 0.4 in T2 (150% K) and 4.0 ± 0.3 in T3 (200% K); however, the differences were not statistically significant ($p = 0.052$). From 11 WAT onwards, significant treatment effects were observed on cluster number ($p = 0.016$). Plants in T1(control) and T2 (150% K) produced significantly more clusters than those in T3. A similar pattern was observed at 13 and 15 weeks ($p = 0.018$ and $p = 0.012$, respectively), where T1(control) consistently recorded the highest number of clusters, and T3(200% K) had the lowest cluster production.

The number of flowers and fruits during the later growth stages was not significantly affected by potassium treatments ($p > 0.05$). At 15 WAT, the total number of harvested fruits showed no significant differences among the treatments ($p = 0.308$), although T1 (control) recorded a numerically higher number of fruits than T2 (150% K) and T3(200% K).

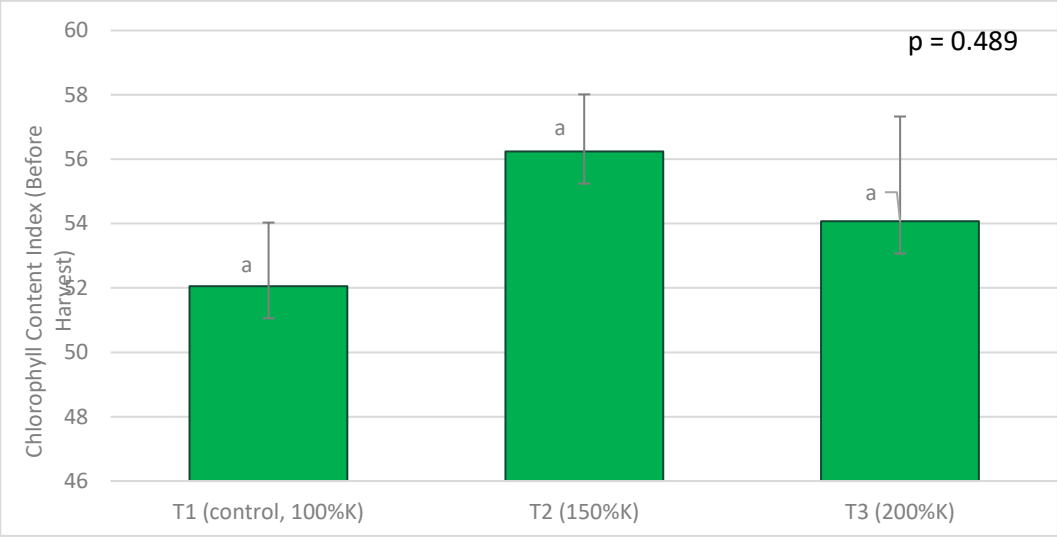
*Table 4. Effect of potassium treatments on reproductive growth parameters of tomato plants at different weeks after transplanting. Values are presented as mean ± standard error (SE) (n = 7). Different superscript letters within the same column indicate significant differences among treatments according to Tukey's HSD test at $p \leq 0.05$. NS = not significant; * = significant at $p \leq 0.05$; *** = significant at $p \leq 0.001$.*

Week After Transplanting (WAT)	Treatment	No. clusters	No. flowers	No. fruits
7	T1 (control)	2.7 ± 0.2	17.0 ± 1.9	0
	T2(150%K)	2.4 ± 0.2	12.9 ± 1.4	0
	T3(200%K)	2.1 ± 0.3	14.7 ± 2.3	0
	p value	0.26 NS	0.327NS	-
9	T1(control)	5.4 ± 0.5	43.0 ± 4.2[a]	2.3 ± 0.9
	T2(150%K)	5.1 ± 0.4	39.6 ± 2.0[ab]	1.3 ± 0.7
	T3(200%K)	4.0 ± 0.3	31.9±1.9[b]	1.3 ± 0.5
	p value	0.052 NS	0.041*	0.542
11	T1(control)	7.0 ± 0.4[a]	20.0 ± 2.8	22.1 ± 1.6
	T2(150%K)	7.0 ± 0.4[a]	22.4 ± 2.2	21.1 ± 1.2
	T3(200%K)	4.0 ± 0.4[b]	23.7 ± 2.1	2.0 ± 2.1
	p value	0.016*	0.546 NS	0.874 NS
13	T1(control)	10.4 ± 0.9[a]	5.6 ± 4.7	46.1 ± 0.5
	T2(150%K)	9.3 ± 0.7[ab]	6.0 ± 3.2	43.4 ± 0.4
	T3(200%K)	7.3 ± 0.3[b]	4.7 ± 0.8	39.1 ± 1.4
	p value	0.018*	0.325NS	0.358NS
15	T1(control)	10.6 ± 2.4[a]	0	50.1 ± 12.5
	T2(150%K)	9.3 ± 1.9[ab]	0	48.6 ± 8.2
	T3(200%K)	7.3 ± 0.8[b]	0	42.9 ± 4.9
	p value	0.012*	-	0.308NS

3.3 Effect of Potassium Enrichment on Leaf Chlorophyll Content

As shown in Figure 2, K enrichment did not significantly affect the chlorophyll content of tomato plants before harvest ($p = 0.489$). The highest chl content was observed in T2 (150% K) (56.24 ± 1.77), followed by T3 (200% K) (54.07 ± 3.25), whereas the lowest value was recorded in T1 (Control) (52.06 ± 1.97). Although T2 (150% K) showed a numerically higher chlorophyll content than the other treatments, this indicates that all treatments belonged to the same statistical group, suggesting that K enrichment did not cause significant changes in chlorophyll accumulation.

Figure 2. Effect of potassium enrichment on chlorophyll content of nine-week-old tomato plants (before harvest) under different potassium treatments (T1 = 100% K, T2 = 150% K and T3 = 200% K). Values represent mean ± standard error (SE) (n = 7). Bars sharing the same letter are not significantly different according to Tukey's HSD test ($p < 0.05$).



As shown in Figure 3, chlorophyll content after harvest was significantly influenced by K enrichment (p = 0.022). Potassium enrichment affected chlorophyll retention after harvest, with T3(200% K) exhibiting higher chlorophyll values than T1(control) . T3 (200% K) (40.70 ± 2.53), followed by T2 (150% K) (33.18 ± 2.17), while the lowest value was observed in T1 (Control) (30.48 ± 2.56). Tukey's HSD test showed that T3 had significantly higher chlorophyll content compared with T1(control) , whereas T2 (150% K) exhibited an intermediate response and did not differ significantly from either T1 (control) or T3(150% K).

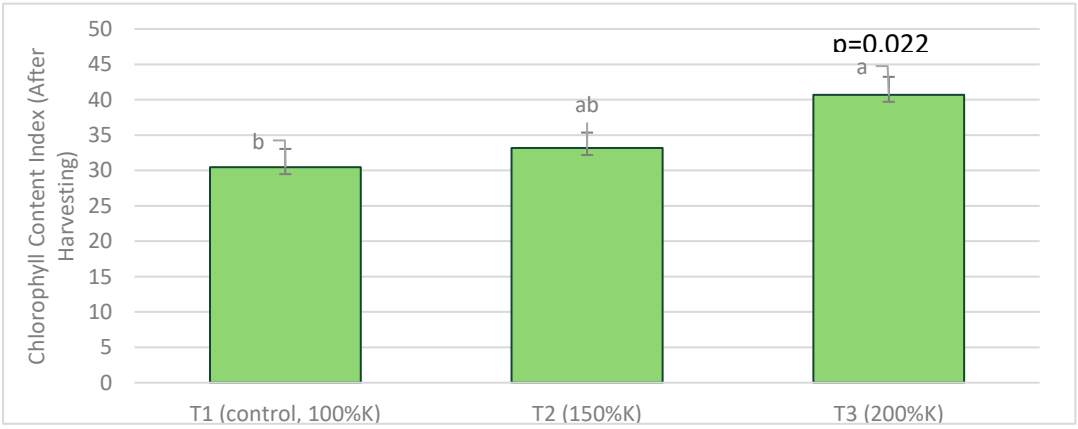


Figure 3. Effect of potassium enrichment on chlorophyll content of fifteen-week-old tomato plants (after harvest) under different potassium treatments (T1 = 100% K, T2 = 150% K and T3 = 200% K).Values represent mean ± standard error (SE) (n = 7). Significant

differences among treatments, whereas bars sharing the same letter are not significantly different according to Tukey's HSD test ($p < 0.05$)

3.4 Effect of Potassium Enrichment on Tomato Yield

As shown in Figure 4, the tomato fruit yield differed significantly among the treatments ($p = 0.044$). The highest yield was obtained from T1 (100% K) 406.64 ± 4.82 g plant^{-1}, followed by T2 (150% K) (382.60 ± 5.09 g plant^{-1}) and T3 (200% K) (374.70 ± 13.16 g plant^{-1}). According to Tukey's HSD test, T1(control) was significantly different from T3(200% K), whereas T2 (150% K) showed an intermediate response and did not differ significantly from either T1 (control,100% K) or T3 (200% K).

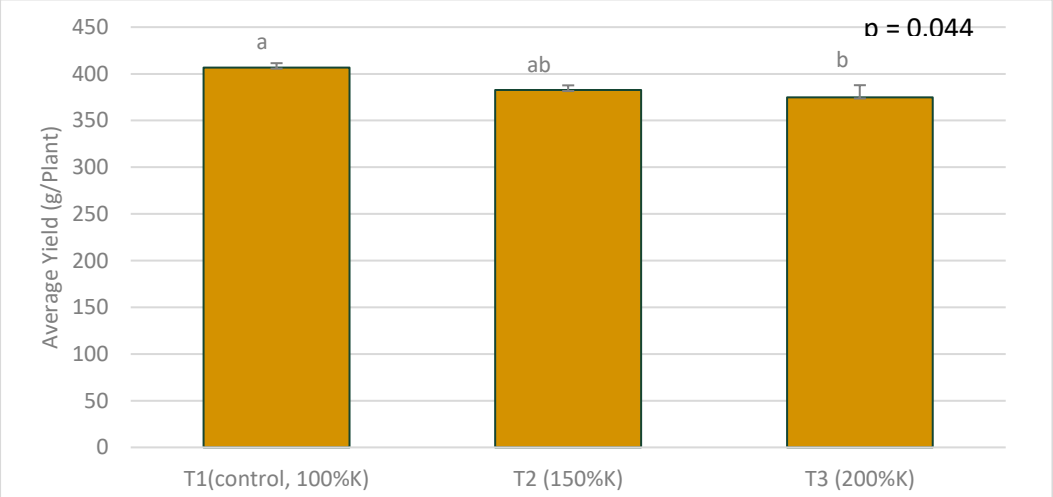


Figure 4. Effect of potassium enrichment on yield under potassium treatments (T1 = 100% K, T2 = 150% K, and T3 = 200% K). Values represent mean ± standard error (SE) (n = 7). Different letters above the bars indicate that bars sharing the same letter are not significantly different according to Tukey's HSD test ($p < 0.05$).

3.5 Effect of Potassium Enrichment on Tomato Fresh Weight

Potassium enrichment did not significantly affect the fresh weight of tomato plants ($p = 0.970$). The mean fresh weight ranged from 125.74 to 127.41 g among the treatments. The highest fresh weight was recorded in T3 (200% K) (127.41 ± 5.18 g), followed by T2 (150% K) (127.12 ± 5.05 g), whereas T1 (control) showed the lowest value (125.74 ± 5.12 g). According to Tukey's HSD test, all treatments were grouped (a), indicating that potassium enrichment did not significantly affect plant fresh biomass (Figure 5).

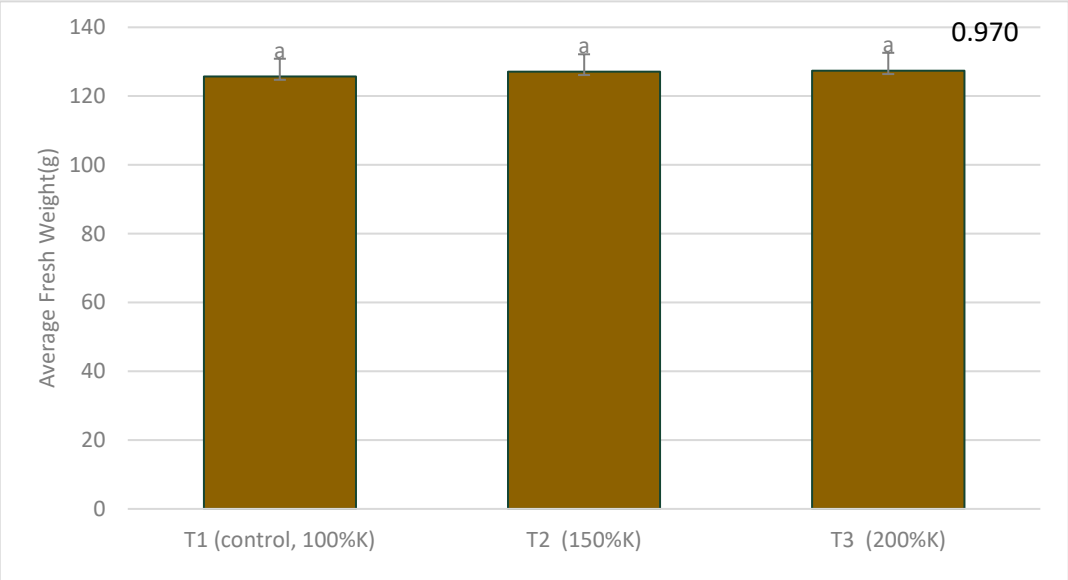
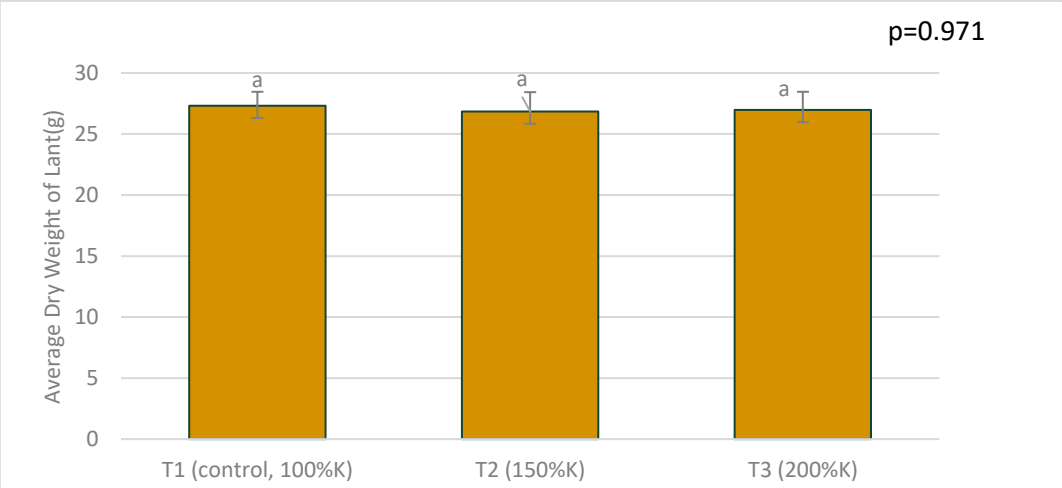


Figure 5. Effect of potassium enrichment on average fresh weight of tomato plants under different potassium treatments (T1 = 100% K, T2 = 150% K and T3 = 200% K). Values represent mean ± standard error (SE) (n = 7). Bars sharing the same letter are not significantly different according to Tukey's HSD test ($p < 0.05$).

3.6 Effect of Potassium Enrichment on Tomato Dry Weight

Figure 6. Effect of potassium enrichment on average dry weight of tomato plants under different potassium treatments (T1 = 100% K, T2 = 150% K and T3 = 200% K). Values represent mean ± standard error (SE) (n = 7). Bars sharing the same letter are not significantly different according to Tukey's HSD test (p < 0.05)



Potassium enrichment did not significantly affect the dry weight of the tomato plants ($p = 0.971$). The mean dry weight ranged from 26.84 to 27.31 g across the treatments. The highest dry weight was recorded in T1 (control) (27.31 ± 1.15 g), followed by T3 (200% K) (26.97 ± 1.49 g), whereas the lowest value was

observed in T2 (150% K) (26.84 ± 1.59 g). According to Tukey's HSD test, all treatments belonged to the same statistical group, indicating that potassium enrichment did not significantly affect the plant dry weight (Figure 6).

3.7 Effect of Potassium Enrichment on pH of Tomato Fruit

As shown in Figure 7, potassium enrichment did not significantly affect the pH of the tomato fruits (p = 0.308). The fruit pH values ranged from 4.05 to 4.14 across the treatments. The highest pH was recorded in T3 (200% K) (4.14 ± 0.02), followed by T1 (Control) (4.10 ± 0.03), whereas T2 (150% K) showed the lowest pH value (4.05 ± 0.05).

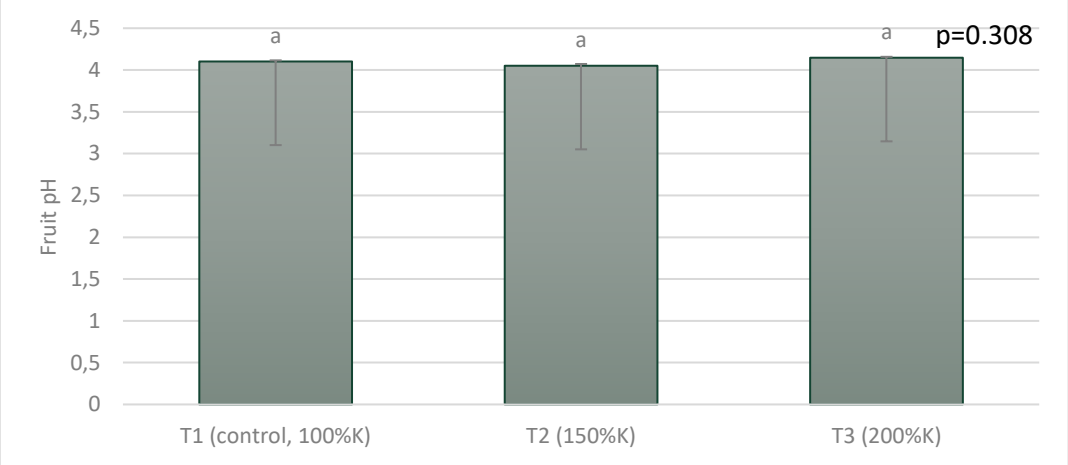


Figure 7. Effect of potassium enrichment on pH of tomato fruits under different potassium treatments (T1 = 100% K, T2 = 150% K, and T3 = 200% K). Values represent mean ± standard error (SE) (n = 7). Bars sharing the same letter are not significantly different according to Tukey's HSD test (p < 0.05)

3.8 Effect of Potassium Enrichment on Total Soluble Solids (TSS) of Tomato Fruit

As shown in Figure 8, potassium enrichment resulted in a slight increase in total soluble solids (TSS) compared with the control treatment; however, the differences among treatments were not statistically significant (p = 0.064). The highest TSS content was observed in T2 (150% K) (6.16 ± 0.08 °Brix), followed by T3 (200% K) (6.05 ± 0.34 °Brix), whereas the lowest value was recorded in T1 (control) (5.77 ± 0.12 °Brix).

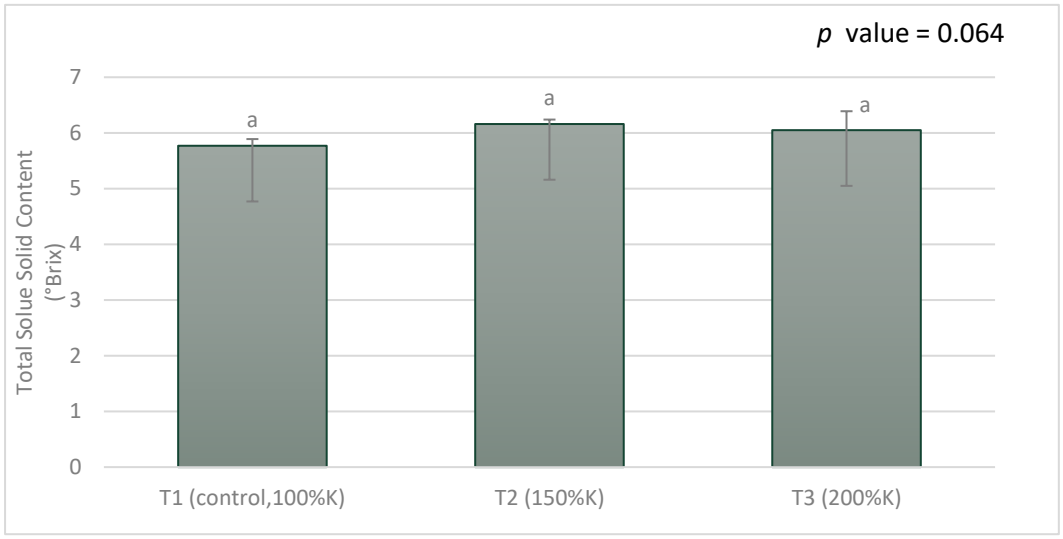


Figure 8. Effect of potassium enrichment on total soluble solids (TSS) of tomato fruits under different potassium treatments (T1 = 100% K, T2 = 150% K and T3 = 200% K). Values represent mean ± standard error (SE) (n = 7). Bars sharing the same letter are not significantly different according to Tukey's HSD test ($p < 0.05$).

3.9. Effect of Potassium Enrichment on Titratable Acidity of Tomato Fruit

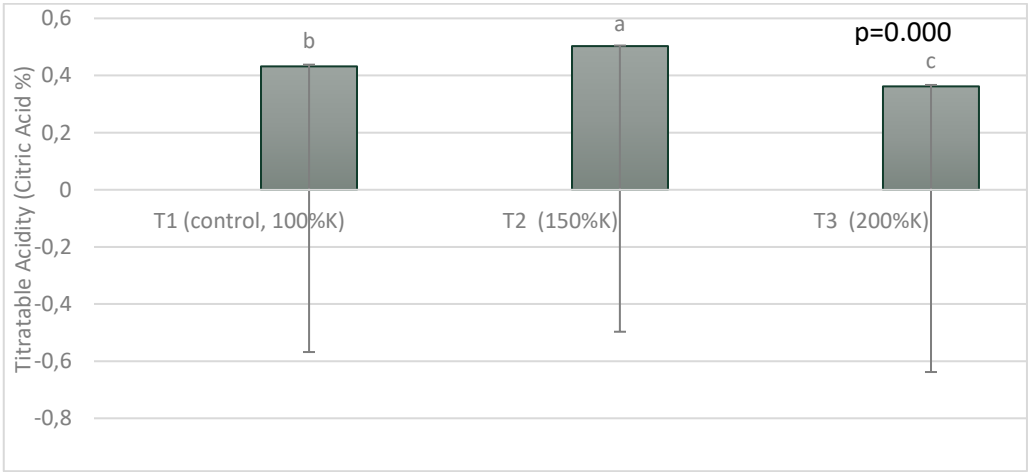


Figure 9. Effect of potassium enrichment on titratable acidity (TA) of tomato fruits under different potassium treatments (T1 = 100% K, T2 = 150% K, and T3 = 200% K). Values represent mean ± standard error (SE) (n = 7). Different letters above the bars indicate significant differences among treatments, whereas bars sharing the same letter are not significantly different according to Tukey's HSD test ($p < 0.05$).

The TA of tomato fruits was significantly affected by K enrichment ($p < 0.001$). The highest TA was recorded in T2 (150% K) (0.50 ± 0.002%), followed by T1 (control), whereas the lowest acidity was observed in T3 (200% K) (0.36 ± 0.005%). Tukey's HSD test revealed that all treatments differed

significantly from each other, with T2 (150% K), T1 (100% K), and T3 (200% K) classified as a, b, and c, respectively (Figure 9).

3.10. Effect of Potassium Enrichment on the Total Soluble Solids to Titratable Acidity Ratio (TSS/TA) of Tomato Fruit

As shown in Figure 10, the TSS/TA ratio of tomato fruits was significantly affected by K enrichment ($p < 0.001$). The highest TSS/TA ratio in tomato fruits was recorded in T3 (200% K) (16.709 ± 0.537), which was significantly higher than that of T1 (Control) (13.359 ± 0.405) and T2 (150% K) (12.37 ± 0.546). According to Tukey's test, T1(control) and T2 (150% K) were statistically similar, whereas T3(200% K)showed a significant difference from both treatments.

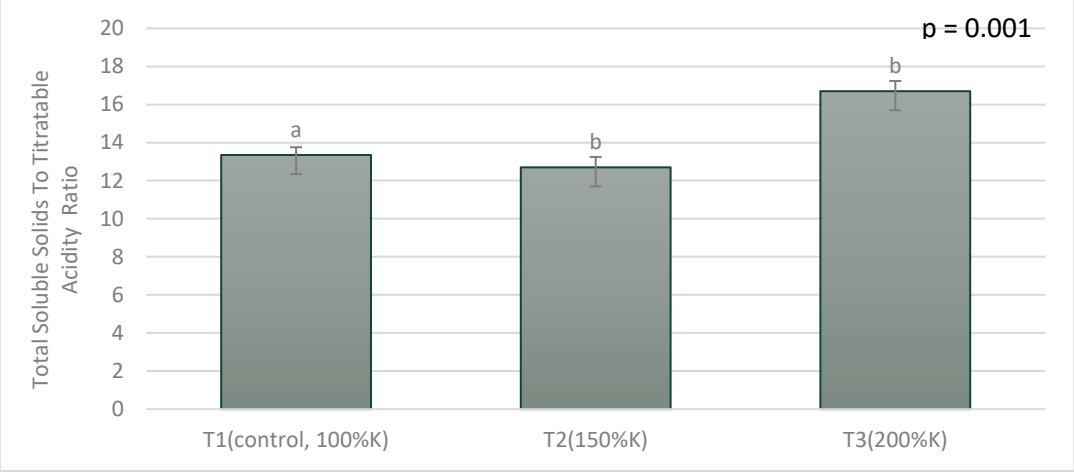


Figure 10. Effect of potassium enrichment on TSS/TA ratio of tomato fruits under different potassium treatments (T1 = 100% K, T2 = 150% K, and T3 = 200% K). Values represent mean ± standard error (SE) (n = 7). Different letters above the bars indicate significant differences among treatments, whereas bars sharing the same letter are not significantly different according to Tukey's HSD test (p < 0.05)

4. DISCUSSION

4.1 Effect of Potassium Enrichment on Vegetative Growth and Physiological Performance of Tomato Plants

Potassium is an essential macronutrient involved in several physiological processes that regulate plant growth and development, including enzyme activation, stomatal regulation, osmotic adjustment, photosynthetic activity, and carbohydrate transport. According to Cakmak (2005), adequate K availability contributes to maintaining cellular functions, improving plant stress tolerance, and supporting efficient production and transport. In the present study, potassium enrichment above the standard concentration of the MHS did not significantly influence tomato plant height throughout the experimental period.

Similarly, the final fresh and dry weights were not significantly affected by potassium treatments. These results indicate that additional potassium supply did not provide measurable improvements in vegetative biomass production under the conditions of this experiment. According to Van Delden et al. (2020), plant performance in a controlled nutrient system is strongly influenced by the overall balance of the nutrient solution, and balance nutrient solution produces optimal growth at appropriate concentrations. The absence of a significant growth response in the present study may be related to the adequate supply of K^+ in the control treatment. The MHS provides approximately 273-274 mg K L^{-1}, which may have been sufficient to meet the K requirements of tomato plants during vegetative growth. Positive responses to potassium fertilization are commonly observed when plants experience potassium deficiency because inadequate potassium availability can reduce photosynthetic CO_2 fixation efficiency, enzyme activity, and restrict carbohydrate transport while increasing oxidative stress and reactive oxygen species, which may result in chlorophyll degradation and growth reduction (Cakmak, 2005). However, when potassium availability is already adequate, additional potassium may have a limited influence on growth because another factor may become more limiting.

The number of leaves showed significant differences at the 9th and 11th weeks after transplanting, with the control treatment generally maintaining higher leaf numbers than the highest potassium treatment. However, these differences were not maintained until the final measurement stage of the study. This indicates that K enrichment did not consistently promote leaf development. Similar observations were reported by Van Delden et al. (2020), who emphasized that excessive modification of individual nutrients in controlled cultivation systems may disturb nutrient relationships and influence plant responses.

One possible explanation for the lower leaf number observed under the highest K treatment is the potential interaction between K and other essential nutrients. Potassium competes with other cations, particularly calcium (Ca) and magnesium (Mg), for uptake sites within the root system. According to Bar-Tal and Pressman (1996), high K availability in greenhouse tomato production can influence Ca nutrition and contribute to nutrient imbalance. Therefore, increasing potassium concentration beyond the optimal level may not necessarily improve vegetative development and may potentially affect nutrient relationships.

Leaf chlorophyll content is commonly used as an indicator of plant physiological status because chlorophyll concentration reflects photosynthetic capacity and nutrient availability (Kamble et al., 2015). In the current study, K enrichment did not significantly affect chlorophyll content before harvest. Although T2 (150% K) tomato showed the highest numerical chlorophyll value, statistical analysis indicated that all treatments belonged to the same group. This suggests that K enrichment did not significantly improve chlorophyll accumulation during active plant growth.

After harvest, the chlorophyll content was significantly higher in T3 (200% K) than in T1 (control). Potassium has been reported to contribute to the maintenance of chloroplast function, regulation of cellular processes, and delay of leaf senescence under certain conditions (Mirza et al., 2013). Nonetheless, it is important to approach the increased chlorophyll retention noted in T3 (200% K) with caution. Although T3 (200% K) maintained higher chlorophyll values at the end of cultivation, this treatment produced fewer clusters and lower fruit yield compared with the control treatment. A possible explanation for this is that plants with lower reproductive demands may retain more chlorophyll because fewer photosynthetic resources are transferred from the leaves to the developing fruits. Therefore, the higher chlorophyll content in T3 (200% K) cannot be considered as direct evidence of improved physiological performance caused by potassium enrichment.

Potassium is expected to support vegetative growth through its role in photosynthesis, enzyme activity, and carbohydrate transport. However, the lack of significant effects on plant height, biomass, and early chlorophyll content suggests that K was not a limiting factor under the conditions of this experiment. The adequate potassium concentration in the control group may explain why further enrichment did not provide additional growth benefits. Although T3 (200% K) showed higher chlorophyll content after harvest, this was not accompanied by improved growth or yield, indicating that higher chlorophyll content did not translate into overall improved plant performance

Overall, the present findings demonstrate that an increase in potassium above the standard Hoagland concentration did not improve vegetative growth, biomass accumulation, or early physiological performance of tomato plants. From a horticultural nutrient management perspective, this study highlights the importance

of maintaining an adequate and balanced nutrient supply rather than increasing potassium concentration beyond crop requirements.

4.2 Effect of Potassium Enrichment on Reproductive Development and Tomato Yield

Potassium plays an important role in reproductive development because it regulates assimilate transport, enzyme activity, water relations, and the movement of carbohydrates from source tissues (leaves) to sink tissues (developing flowers and fruits). According to Cakmak (2005), K contributes to efficient photosynthesis and carbohydrate metabolism, which are essential processes for reproductive growth. Previous studies have reported that adequate K availability can improve flowering, fruit development, and yield formation in tomato plants, particularly when K availability is limited. (Javaria et al.,2012; Çolpan et al.,2013). However, the response to K application depends on the existing nutrient status, environmental conditions, and balance among essential nutrients.

In the present study, K enrichment influenced some reproductive parameters, particularly flower production and cluster formation. At the 9th WAT, the number of flowers was significantly affected by the potassium treatments, with the control treatment producing the highest number of flowers and the highest potassium treatment producing the lowest number. Although flower development is influenced by several factors, including plant developmental stage, environmental conditions, cultivar characteristics, and nutrient availability, these results indicate that increasing the potassium concentration above the standard nutrient level did not enhance flower production under the conditions of this experiment.

Cluster formation showed a similar response pattern. From the 11th week onwards, plants grown under the control and moderate K treatments produced significantly more clusters than those under the high K treatment. As clusters represent potential sites for fruit formation, the reduced cluster number observed under T3 may have contributed to the lower final yield recorded in this treatment. K is generally associated with improved reproductive development through enhanced carbohydrate transport and improved water regulation (Javaria et al., 2012). However, excessive potassium supply may not provide additional benefits when plants already receive sufficient K.

The number of harvested fruits was not significantly influenced by the potassium treatments, although the control treatment showed a numerically higher fruit number than T2 (150% K) and T3 (200% K). The number of fruits is determined by several physiological processes, including flower initiation, pollination success, fruit set, and fruit retention. Therefore, the absence of significant differences in fruit numbers suggests that potassium enrichment alone was not a major limiting factor affecting final fruit production in this study. Tomato fruit yield was significantly influenced by potassium treatments. The control treatment recorded the highest

yield (406.64 ± 4.82 g plant^{-1}), whereas the highest K treatment showed the lowest yield (374.70 ± 13.16 g plant^{-1}). Moderate potassium treatment showed an intermediate response and was not significantly different from either the control or the highest K treatment. These results indicate that increasing the potassium concentration above the standard Hoagland level did not improve tomato yield under the tested greenhouse conditions.

The present findings differ from those of studies in which K application improved tomato yield. For example, Javaria et al. (2012) and Çolpan et al. (2013) reported the positive effects of potassium fertilization on tomato yield and quality characteristics. However, these responses were observed under conditions where potassium availability may have been more limiting. In contrast, the current experiment was conducted using an MHS containing an adequate K concentration in the control treatment. Therefore, additional potassium may not have increased the yield because the plants had already received sufficient potassium for normal reproductive development.

The reduction in yield observed under T3 (200% K) should be interpreted with caution. Although the highest potassium treatment showed the lowest cluster number and yield, the results cannot confirm that the potassium concentration alone was responsible for this reduction. The addition of potassium sulfate can influence the overall ionic composition of the nutrient solution, and excessive potassium availability may affect the uptake balance of other essential nutrients, particularly calcium and magnesium. (Bar-Tal and Pressman, 1996) nutrient interactions are particularly important in greenhouse production systems, where plants depend entirely on the supplied nutrient solutions.

Purple to Violet leaf discoloration was observed in all treatments around the 9th WAT, following flower initiation. Symptoms appeared with similar intensity among the treatments and did not progressively increase during the remaining cultivation period. According to Savvas et al. (2008), these symptoms are commonly associated with phosphorus deficiency or restricted phosphorus availability, and low temperatures can reduce phosphorus uptake by limiting root activity. In this study, the irrigation water temperature was 14 -15 °C, which may have affected phosphorus uptake. However, phosphorus deficiency was not confirmed because tissue analysis was not conducted, and root zone temperature was not directly measured. The irrigation schedule was changed from 5:00 PM to approximately 3:00 PM to reduce the potential impact of cool water. Therefore, these symptoms are considered a possible indication of limited phosphorus availability rather than a confirmed deficiency.

Potassium is expected to support flowering, cluster formation, and yield through its role in carbohydrate transport and reproductive development. However, the present results did not support this expected positive response, as the control produced more flowers and clusters, whereas T3 (200% K) showed the lowest cluster number and yield. The lower cluster formation may have contributed to the

reduced yield under T3 (200% K) treatment. However, the specific mechanism cannot be confirmed because nutrient uptake and tissue nutrient concentrations were not measured in this study. The difference from previous studies reporting a positive effect of potassium on tomato yield may be related to differences in initial K availability and growing conditions, as the control treatment in the present study already received an adequate potassium concentration

From a horticultural perspective, these findings indicate that maximizing potassium input may not necessarily enhance tomato reproductive performance. Instead, efficient nutrient management should focus on maintaining an optimal nutrient balance according to the crop demand. Excessive fertilizer application may increase production costs without providing yield benefits and may reduce nutrient-use efficiency. Therefore, sustainable greenhouse tomato production requires precise potassium management rather than simply increasing the potassium concentration.

4.3 Effect of Potassium Enrichment on Tomato Fruit Quality, Flavour Balance and Consumer Preference

Fruit quality has become an increasingly important objective in modern tomato production because market value and consumer acceptance depend not only on yield but also on desirable eating characteristics. Consumers generally evaluate tomatoes based on a combination of sweetness, acidity, flavor intensity, texture, appearance, and overall acceptability. Therefore, horticultural production systems must consider both productivity and quality attributes when developing nutrient-management strategies. According to Amr and Raie (2022), tomato fruit quality is determined by complex interactions among biochemical compounds, including sugars, organic acids, pigments, antioxidants, and flavor-related compounds.

Potassium is considered an important nutrient for tomato fruit quality development because it regulates carbohydrate transport, enzyme activity, osmotic adjustment, and water movement within plant tissues. Previous investigations have reported that K availability can influence soluble solids accumulation, acidity, and other fruit quality characteristics. For example, Javaria et al. (2012) reported that potassium application influenced the chemical and sensory characteristics of tomato fruits, whereas Çolpan et al. (2013) demonstrated that potassium supply influenced yield and fruit quality components. However, the response of fruit quality to potassium depends on the initial nutrient status of the plants, cultivar characteristics, and environmental conditions.

4.4 Effect of Potassium Enrichment on Total Soluble Solids (TSS)

Total soluble solids (TSS), expressed as °Brix, are commonly used as an indicator of soluble sugar concentration and are an important component of tomato sweetness perception (Portugal et al., 2015). In the present study, K enrichment resulted in a numerical increase in TSS compared to the control treatment. However, these differences were not statistically significant ($p = 0.064$). The highest TSS value was observed in T2 (150% K) (6.16 ± 0.08 °Brix), followed by T3 (200% K) (6.05 ± 0.34 °Brix), whereas T1 (control) recorded the lowest value (5.77 ± 0.12 °Brix).

Although T2 (150% K) showed a tendency towards higher soluble solids accumulation, statistical analysis indicated that potassium enrichment did not provide sufficient evidence to confirm improved sugar accumulation. This finding differs from those of previous studies, in which potassium application increased the TSS content in tomato fruits (Javaria et al., 2012; Çolpan et al., 2013). This difference may be explained by the adequate potassium supply already provided in the control treatment through the use of the MHS. When potassium availability is sufficient, additional potassium may have a limited influence on carbohydrate accumulation because potassium is no longer the main factor limiting sugar transport and fruit development.

From a horticultural perspective, this finding is important because it demonstrates that applying additional potassium fertilizer does not always improve fruit sweetness. Therefore, efficient nutrient management should focus on identifying the optimum potassium level rather than increasing fertilizer inputs without clear benefits.

4.5 Effect of Potassium Enrichment on Titratable Acidity (TA)

Titratable acidity represents the concentration of organic acids, mainly citric and malic acids, which contribute to tomato flavor by providing characteristic acidity and balance in sweetness (Moneruzzaman et al., 2008). In contrast to TSS, TA was significantly affected by potassium enrichment in the present study. The highest acidity was recorded in T2 (150% K) (0.50 ± 0.002%), followed by T1 (Control), whereas T3 (200 % K) showed the lowest acidity (0.363 ± 0.005%). All treatments were statistically different according to Tukey's HSD test. This result indicates that potassium enrichment altered the TA of tomato fruit, with moderate potassium enrichment (150%K) increasing acidity, whereas excessive potassium enrichment (200 % K) resulted in lower acidity than that of the control.

These results indicate that potassium enrichment influences organic acid accumulation and metabolism in tomato fruits. Changes in fruit acidity may occur

because nutrient availability affects carbohydrate metabolism, organic acid synthesis, and fruit maturation. Similar effects of K nutrition on the chemical and sensory attributes of tomato fruits have been reported by Javaria et al. (2012). However, the exact physiological mechanism responsible for the observed differences in acidity cannot be confirmed from the present study alone. Additional analyses of organic acid composition and nutrient accumulation are required to explain these changes more precisely.

4.6 Effect of Potassium Enrichment on TSS/TA Ratio and Flavour Balance

The TSS/TA ratio is commonly used as an indicator of sweetness-acidity balance and is considered an important maturity- and flavor-related quality index in tomato fruits (Moneruzzaman et al., 2008). In the present study, potassium enrichment significantly affected the TSS/TA ratio, with T3 (200% K) recording the highest ratio, followed by T1 (control) and T2 (150% K). Although T3 (200% K) showed the highest TSS/TA ratio, this result should be interpreted with caution. The higher TSS/TA ratio in T3 (200% K) was mainly caused by the substantially lower TA rather than the increased soluble solids content. Therefore, a higher TSS/TA ratio does not necessarily indicate superior flavor quality. A reduction in acidity may result in a less acidic taste, but it does not automatically mean that consumers will prefer the fruit. According to Baldwin et al. (2000), tomato flavor perception is a complex process influenced by the interaction between sugars, organic acids, and volatile aroma compounds.

Therefore, chemical indicators such as TSS and the TSS/TA ratio provide useful information but cannot completely predict consumer preference. As sensory evaluation was not conducted in this study, determining whether T3 (200% K) resulted in the most preferred flavor profile was not feasible.

4.7 Effect of Potassium Enrichment on Fruit pH

Fruit pH is another important quality parameter because it reflects the hydrogen ion concentration and contributes to the perception of acidity. In the present study, K^+ enrichment did not significantly affect the pH of tomato fruit ($p = 0.308$). The pH values remained within a narrow range among the treatments, indicating that K supply did not substantially modify the overall acidity of tomato fruits. The absence of significant differences in pH, while TA showed significant variation, highlights the importance of measuring both parameters. pH represents free hydrogen ion activity, whereas TA reflects the total concentration of organic acids contributing to the flavor. Therefore, TA may provide a more meaningful indication of flavor-related acidity changes in tomato fruits.

4.8 Overall Implication for Fruit Quality and Consumers' Acceptance

In the present study, K affected fruit quality by influencing carbohydrate transport and organic acid metabolism; however, the response was parameter-dependent. TSS showed only a numerical increase and was not statistically significant, indicating that additional K did not provide sufficient evidence for improved sugar accumulation or sweetness. In contrast, TA was significantly affected, with T3(200% K) showing lower acidity than T2 (150% K), indicating a change in the fruit acidity. Although T3 (200% K) had the highest TSS/TA ratio, this was mainly due to its low acidity rather than increased TSS and therefore does not demonstrate improved sweetness or flavor. Fruit pH was not significantly affected, further indicating that K did not produce a uniform change in all measures of fruit quality.

This indicates that K supply may influence the flavor balance of tomatoes primarily through changes in acidity rather than soluble solids. Similar effects of K nutrition on the chemical and sensory attributes of tomato fruits have been reported by Javaria et al. (2012). Therefore, selecting a K treatment based on a single quality parameter may lead to incorrect conclusions.

From a horticultural and consumer perspective, the ideal fertilization strategy should achieve a balance between yield, sweetness, acidity, and flavor perception. These results suggest that maintaining an adequate K concentration may be more beneficial than applying excessive K in an attempt to improve fruit quality. Future studies incorporating sensory evaluation, aroma analysis, and consumer acceptance testing would provide a more comprehensive understanding of how potassium management influences tomato market quality.

4.9 Importance of Potassium Management for Sustainable Greenhouse Tomato Production

These findings have implications for sustainable production. Sustainable greenhouse tomato production requires balanced nutrient management to achieve high yields, desirable fruit quality, and efficient resource use. However, the present study showed that an increase in K above the standard Hoagland concentration did not improve vegetative growth, fruit sweetness, or overall yield. These findings support the importance of optimizing rather than maximizing K application. According to Van Delden et al. (2020), balanced nutrient ratios are more important than increasing individual nutrients, whereas excessive K may interfere with Ca and Mg uptake (Bar-Tal & Pressman, 1996). Therefore, precision nutrient management can improve fertilizer use efficiency, reduce unnecessary inputs and production costs, and support sustainable greenhouse tomato production while maintaining fruit quality.

4.10 Limitations of the study

Several limitations should be considered when interpreting the findings of this study. First, the experiment was conducted under controlled greenhouse conditions using a single tomato cultivar and a limited number of biological replicates, which may restrict the generalizability of the results to other cultivars and production systems. Second, only three K levels were evaluated, limiting the ability to determine the precise optimum K concentration for tomato production. Third, the additional potassium sulphate supplied approximately 148 and 274 mg L^{-1} K and 182 and 336 mg L^{-1} SO_4^{2-} in T2 (150% K) and T3 (200% K), respectively. Therefore, the observed responses cannot be considered the only effect of potassium. Because increased sulphate availability may have influenced plant growth, nutrient uptake, and fruit quality parameters. Future studies should consider using nutrient formulations that maintain constant sulphate concentrations and EC levels across treatments to better isolate the specific effect of potassium. In addition, tissue nutrient concentrations were not analyzed; consequently, possible interactions between K and other nutrients, particularly calcium, magnesium, and phosphorus, could not be confirmed. The organic acid composition was not directly measured, limiting the interpretation of changes in TA. Although trays were used to retain drainage and minimize nutrient losses, drainage volume, EC, and pH were not measured during the experiment; this also represents a limitation of the study, as the actual root zone nutrient and salinity conditions could not be determined. Finally, sensory evaluation and volatile compound analysis were not conducted; therefore, consumer preference and flavor perception could not be directly assessed.

4.11 Recommendations

According to the results of this study, K fertilization should be adjusted to the crop's specific needs. It should not be increased beyond a sufficient nutrient level unless there is clear evidence of further benefits. Future studies should evaluate a wider range of K concentrations, including levels below and around the standard nutrient concentration, to identify the optimum K supply for greenhouse tomato production. Future research should measure tissue concentrations of K and other essential nutrients to determine whether nutrient interactions contribute to growth, yield, and fruit quality responses. Analysis of individual organic acids and soluble sugars would help clarify the physiological basis for changes in TA and the TSS/TA ratio. In addition, sensory evaluation and volatile compound analysis are recommended to determine whether changes in the chemical fruit quality parameters correspond to differences in the perceived flavor and consumer acceptance.

5. CONCLUSION

This study evaluated the effect of potassium enrichment on tomato growth, yield, and fruit quality under greenhouse conditions. Potassium treatments significantly affected cluster number, fruit yield, chlorophyll content after harvest, titratable acidity, and total soluble solids-to-titratable acidity ratio. Potassium treatments did not significantly affect plant height, biomass production, fruit number, fruit pH, total soluble solids, andresearch chlorophyll content before harvest. However, these responses should not be attributed solely to potassium enrichment, as the treatments also involved changes in nutrient composition and electrical conductivity. The control treatment produced the highest yield, whereas the highest potassium treatment reduced cluster number and yield. Although 200% potassium had the highest total soluble solids-to-titratable acidity ratio, this was mainly due to lower acidity rather than increased sweetness. Therefore, potassium enrichment above the standard Hoagland concentration did not improve tomato growth or yield and did not provide clear benefits for most fruit quality parameters under the tested greenhouse conditions. These findings highlight the importance of balanced nutrient management for greenhouse tomato production.

POPULAR SCIENCE SUMMARY



‘Can more potassium make tomatoes better?’
This study examined how different potassium levels influenced tomato growth, yield and fruit quality under greenhouse conditions. In this experiment, 21 tomato plants were exposed to three potassium level treatments at 100%(control), 150%, and 200% of the standard level. During the experiment, plant height, leaf number, flowers, clusters, biomass and yield were recorded. Fruit quality was evaluated by measuring total soluble solids, titratable acidity, pH, and the total soluble solids-to-acidity ratio. Total soluble solids indicated the sweetness of the fruit, while titratable acidity indicated the sourness of the fruit. The total soluble solids-to-titratable acidity ratio indicated the flavor balance. Surprisingly, increasing potassium did not show better performance in plant growth and yield. The standard potassium level showed the highest yield and growth performance, while the highest potassium showed a higher flavour balance between sweetness and acidity. However, the total soluble solids to titratable acidity ratio increased due to lower acidity, rather than higher sweetness. Finally, the results showed that more potassium is not always better and an appropriate potassium level is important for tomato production.

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