The Impact of Ammonium Fertilization on Growth and Quality Parameters of Tomato Plant Grown under Greenhouse Condition

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Abstract

Nutrient management is an important for improving productivity and fruit quality in horticultural crops, as the form and availability of essential nutrients can influence plant growth, yield formation and the accumulation of quality related compounds. Nitrogen plays an important role in balancing plant growth, yield and fruit quality in tomato. The balance between nitrate (NO_3^-) and ammonium (NH_4^+) can influence vegetative development, reproductive performance and fruit quality. This study evaluated the effects of different NO_3^-: NH_4^+ ratios on the growth, chlorophyll content, yield and fruit quality of Sweet Sturdy™ Jo F1 tomato grown under greenhouse conditions. The experiment was conducted using a completely randomized design with three nitrogen treatments and seven biological replicates per treatment. Plants were grown in a pumice based growing medium and supplied with modified Hoagland nutrient solutions containing 100% NO_3^-:0% NH_4^+ (T1), 50% NO_3^-:50% NH_4^+ (T2) and 38% NO_3^-:62% NH_4^+ (T3), while maintaining the total nitrogen concentration at 266 mg L^{-1}. Plant growth and reproductive development were monitored during the experiment. Chlorophyll content, biomass, fruit yield and fruit quality attributes, including total soluble solids (TSS), titratable acidity (TA) and sugar to acid ratio, were evaluated. Nitrogen treatment significantly affected later leaf production, reproductive development, biomass production and fruit yield. The treatment without ammonium produced significantly more leaves during the later growth stages and showed the highest fruit yield, with total fruit weight of 358.6 ± 7.6 g per plant, compared with 270.3 ± 7.7 g per plant in 50% ammonium treatment and 219.5 ± 5.3 g per plant in high ammonium treatment. Chlorophyll content did not differ significantly among treatments. 50% ammonium treatment recorded the highest TSS (6.67 ± 0.19 °Brix) and sugar to acid ratio (23.00 ± 1.30), while the treatment without ammonium recorded the highest titratable acidity (0.48 ± 0.01). High ammonium treatment generally showed intermediate fruit quality values. Overall, the treatment without ammonium supported greater plant development, biomass production and fruit yield, while an intermediate ammonium treatment resulted in higher soluble solids and higher sugar to acid balance. Increasing the ammonium proportion to 62% did not provide additional benefits in fruit quality and was associated with reduced growth and yield under the conditions of this experiment. However, the treatments differed not only in NO_3^-:NH_4^+ ratio but also in nutrient solution EC and the concentrations of related ions, particularly sulfate and chloride.

Keywords*:* tomato, *Solanum lycopersicum*, nitrate, ammonium, greenhouse cultivation, fruit quality, yield, total soluble solids, titratable acidity, sugar to acid ratio

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Abbreviations

Abbreviation	Description
$(NH_4)_2SO_4$	Ammonium Sulfate
ANOVA	Analysis of Variance
ATP	Adenosine Triphosphate
$Ca(NO_3)_2 \cdot 4H_2O$	Calcium Nitrate Tetrahydrate
$CaCl_2.2H_2O$	Calcium Cloride Dehydrate
CCI	Chlorophyll Content Index
Cl^-	Chloride ion
cm	Centimeter
CRD	Completely Randomized Design
$CuSO_4 \cdot 5H_2O$	Copper sulfate pentahydrate
^oC	Degrees Celsius
dS m^{-1}	deci Seimens per meter
EC	Electrical Conductivity
EDTA. 2Na	Ethylene dia amine tetra acetic acid
Fe-EDTA	Iron chelate
FeSO4.7H2O	Iron sulphate hepta hydrate
g	grams
H^+	Hydrogen ion
H_3BO_3	Boric acid
HSD	Honestly Significant Difference
K	Potassium
KH_2PO_4	Monopotassium phosphate
KNO_3	Potassium nitrate
KOH	Potassium hydroxide
L	Liter
M	Molar
m^2	Square meters
$MgSO_4 \cdot 7H_2O$	Magnesium sulphate heptahydrate
mL	mililiter
$MnCl_2 \cdot 4H_2O$	Manganese chloride tetrahydrate
N	Nitrogen
$Na_2MoO_4 \cdot 2H_2O$	Sodium molybdate
NaOH	Sodium hydroxide
NH_4^+	Ammonium ion

NO_3^-	Nitrate ion
P	Phosphorus
pH	Potential of Hydrogen
RH	Relative Humidity
SE	Standard Error
SLU	Swedish University of Agricultural Sciences
SO_4^{2-}	Sulfate ion
T1	Treatment 1 (100% nitrate: 0% ammonium)
T2	Treatment 2 (50% nitrate: 50% ammonium)
T3	Treatment 3 (38% nitrate: 62% ammonium)
TA	Titratable Acidity
TDS	Total Dissolved Solids
TSS	Total Soluble Solids
USA	United States of America
W	Watt
WAT	Week After Transplanting
$ZnSO_4 \cdot 7H_2O$	Zinc sulfate heptahydrate

1. Introduction

1.1 Background of Study

Tomato quality is closely linked with nutritional health, societal and consumer aspects. Tomatoes are widely recognized as an important component of a healthy diet and are rich in antioxidant lycopene, β-carotene, vitamin C, pro-vitamin A, folate and minerals such as potassium and secondary metabolites including flavonoids, phytosterols and polyphenols (Ali et al., 2020). Among these compounds, lycopene is the responsible carotenoid for the characteristic red color of ripe tomato fruits and has received considerable attention because of its antioxidant activity and its potential role in reducing the risk of cardiovascular disease and several types of cancer (Vardanian et al., 2025). Also, these compounds help to protect against oxidative stress and may reduce the risk of diabetes, neurodegenerative disorders, improve immune system and skin health (Collins et al., 2022).

Consumer perspective is shaped by both external and internal attributes with tomato products. External attributes such as price, production methods, certification labels and health and environmental sustainability. On the other hand, color, flavor, sweetness and firmness are directly evaluated by consumers, therefore serve as acceptance and purchasing decisions. Research has shown that internal attributes remain the primary factors of consumer acceptance, while external characteristics add value when they meet consumer expectations and improve awareness of product quality (Mancuso et al., 2024).

Today, consumers are becoming increasingly interested in agricultural practices that support sustainable food production from a societal perspective. Agricultural management practices should be balancing productivity and environmental sustainability while maintaining nutritional and sensory qualities. Purchasing decisions of different consumer groups are affected differently by environmental factors. For most people, personal health benefits and product quality are more important than environmental concerns. Therefore, improving tomato quality through efficient nutrient management can provide not only consumer satisfaction but also with more sustainable horticultural production systems (Mancuso et al., 2024).

Nutrient fertilization is a main factor influencing tomato growth, yield and quality of tomato fruit. Balanced nutrient management ensures sufficient plant nutrition while promoting the accumulation of compounds for the nutritional and sensory quality of tomato fruits. Unbalanced nutrient solutions applications can

reduce fertilizer use efficiency, increase production costs, also negatively affect the growing medium, fruit quality and environmental sustainability. Therefore, high quality tomatoes can be produced using balanced nutrients application according to plant nutrient requirements.

Balanced fertilization application involves supplying correct proportions of nitrogen (N), phosphorus (P), potassium (K) and micronutrients based on crop nutrient requirements and the fertilizer use efficiently. It also improves soil fertility, crop productivity and supports agricultural production with sustainability. In tomato cultivation, balanced nutrient management has been identified as an effective strategy for improving fruit quality while minimizing the effect of excess fertilizer application (Li et al., 2024).

Fruit quality is mostly influenced by sugar and acid in fruits which determine sweetness and flavor (Gutierrez, 2018). Application of nutrients with balance amount can increase glucose and fructose level and reduce organic acids, including citric, malic and acetic acids in fruits. It causes to increase sweetness, sugar to acid ratio and overall flavor quality. Research has shown enzymes that regulate sugar synthesis, transport and accumulation in tomato fruits are stimulated with balance nutrients application (Li et al., 2024).

Nitrogen (N) is one of the most important essential macronutrients required for all organisms it forms a structural component of amino acids, proteins, nucleic acids, chlorophyll molecules, ATP and numerous enzymes involved in plant metabolism (Ohyama, 2010). Since nitrogen participates in almost every physiological and biochemical process, its availability directly influences vegetative growth, biomass production, photosynthesis, nutrient utilization, yield and fruit quality (Marschner, 2012). Tomato yield and quality are controlled not only by their genes but also by environmental factors, such as moisture, nutrients, climatic conditions and agricultural practices (Li et al., 2021).

There are two major nitrogen form absorb by plants as nitrate (NO_3^-) and ammonium (NH_4^+), although small quantities of dissolved organic nitrogen may also be utilized under certain environmental conditions (Marschner, 2012). The availability of these nitrogen forms depends on substrate properties, microbial activity, fertilizer type and cultivation system (Britto & Kronzucker, 2006). However, the uptake, transport, assimilation and physiological effects of these two nitrogen forms differ considerably (Marschner, 2012). Consequently, the nitrate to ammonium ratio supplied to plants has influence on root development, nutrient uptake, photosynthesis, biomass production, fruit yield and fruit quality (Wang et al., 2024).

Research demonstrated that high ammonium concentrations in inert substrates can initially limit tomato growth and induce physiological stress, emphasizing the need for carefully balanced nitrogen regimes (Asp & Bergstrand, 2024). In present experiment, the focus is on how nitrate to ammonium ratios affect growth, yield and quality parameters of tomato plants.

1.2 Research gap

Tomato domestication significantly increased fruit yield, the most interesting observation has been the increase in fruit size which was associated with a reduction in sugar content and flavor (Prudent et al., 2009). The improvement of consumers' standard of living worldwide, they prefer delicious fruits are willing to pay a reasonable extra amount for enhanced quality. This has resulted in a shift from yield oriented to flavor oriented cultivation, with flavorful tomato fruits becoming the goal of researchers (Wang et al., 2023).

Therefore, the effects of individual nitrogen forms have been studied, the optimal balance between nitrate and ammonium for improving tomato fruit quality while maintaining plant productivity remains unclear, particularly under greenhouse cultivation systems using soilless substrates. Excessive ammonium supply may negatively affect plant growth due to ammonium toxicity, while a suitable proportion of ammonium can enhance nitrogen use efficiency and potentially improve fruit quality attributes (Yang et al., 2025).

In addition, studies have shown that nitrogen form can significantly affect tomato taste without changing total nitrogen supply (Heeb et al., 2005). However, most studies have focused on soil based systems. There is a need to examine soilless cultivation, where nutrient availability can be precisely controlled, to determine how nitrogen form influences sweetness, physiological performance, yield and fruit quality in greenhouse grown tomatoes.

Even though ammonium effects on tomato growth and quality have been investigated, less information is available regarding ammonium and nitrate ratio under control environment conditions pumice as a growing media. Previous studies have examined ammonium and nitrate ratio together with other factors making it difficult to determine the specific contribution of ammonium to fruit quality. Therefore, research under control of nutritional conditions is required to understand how ammonium concentrations affect tomato fruit quality, growth and for the other plant performances.

1.3 Overall goal

The overall goal of this study was to evaluate the effects of different nitrate (NO_3^-) to ammonium (NH_4^+) ratios on the growth and quality parameters of tomato under greenhouse conditions. Specifically, to determine whether the combined application of nitrate and ammonium could improve plant growth and fruit quality attributes.

1.4 Objective

To evaluate the effects of different NO_3^- : NH_4^+ ratio on the growth and chlorophyll content of tomato under greenhouse conditions.
To determine NO_3^-: NH_4^+ ratio on the yield and fruit quality of tomato under greenhouse conditions.

1.5 Research Questions

1. How does different NO_3^- : NH_4^+ ratios affect the growth and chlorophyll content of under greenhouse conditions?
2. What are the effects of different NO_3^- : NH_4^+ ratios on the yield of tomato?
3. How does different NO_3^- : NH_4^+ ratios influence the fruit quality of tomato?

1.6 Hypothesis

1.6.1 Null Hypothesis (H_0)

Different NO_3^- : NH_4^+ ratios in the nutrient solution have no significant effect on the growth, yield or fruit quality parameters of Sweet Sturdy™ Jo F1 tomato grown under greenhouse conditions.

1.6.2 Alternative Hypothesis (H_1)

Different NO_3^-:NH_4^+ ratios in the nutrient solution significantly affect the growth, yield and fruit quality parameters of Sweet Sturdy™ Jo F1 tomato grown under greenhouse conditions.

1.7 Limitations of the Study

In this study, Sweet Sturdy™ Jo F1 cultivar was focused on nitrate and ammonium ratios and findings may not be applicable to other varieties. Also, only three treatments were focused, limiting the identification of the optimal nitrogen ratio. The experiment was conducted for three months, it is relatively short period of time which may not reflect long term effect on plant growth, yield and quality attributes.

Ammonium was supplied using ammonium sulfate, while calcium nitrate was partially replaced and calcium was compensated using calcium chloride. Consequently, sulfate and chloride concentrations differed among the treatments, and their potential contribution to plant responses cannot be completely excluded.

The study evaluated plant growth, chlorophyll content, biomass, yield and selected fruit quality characteristics. However, physiological mechanisms essential the treatment responses were not directly evaluated. Measurements such as nutrient uptake, tissue nitrogen and calcium concentration, photosynthetic activity, root development and organic acid or individual sugar composition could provide further understanding into the mechanisms responsible for the observed differences.

In addition, fruit flavor was assessed using chemical quality indicators such as total soluble solids (TSS), titratable acidity (TA) and sugar to acid ratio rather than sensory evaluation. Therefore, the results should be interpreted in terms of measured fruit quality attributes rather than direct consumer perception of flavour.

Finally, the experiment was conducted using a pumice based soilless growing medium under greenhouse conditions with controlled environmental factors. Responses under field conditions or in other growing media may differ. Therefore, further experiments involving a wider range of NO_3^- ratios, multiple cultivars, controlled nutrient solution EC, repeated growing seasons and physiological measurements would be useful to determine the optimum nitrogen form combination for balancing tomato growth, yield and fruit quality.

2. Materials and Methods

2.1 Location

The experiment was conducted for a period of three months, at the greenhouse facility located at the Vegetum, Department of the of Biosystems and Technology, Swedish University of Agricultural Sciences (SLU), Alnarp, Sweden. The temperature was maintained approximately between 18 - 26 ºC, with ventilation setpoint adjusted from 22 ºC to 20 ºC during the experiment and relative humidity was between 25 - 100%. The day length was set as 16h total with the two artificial lamps (400W SON-T high pressure sodium lamps) that were daily turned on at 06h00 and turned off at 22h00. The greenhouse was equipped with an automated environmental control system in which ventilation and temperature were regulated automatically throughout the experimental period. Irrigation and nutrient application were performed manually in experimental period.

2.2 Materials

Tomato plants (*Solanum lycopersicum* cv Sweet Sturdy™ Jo F1) were cultivated in 2 L plastic pots which were placed on top of 9 m^2 tables inside the greenhouse. Pumice was used as the growing medium. The tomato variety chosen for this study was the Sweet Sturdy™ Jo F1 hybrid variety, characterized as being sweet, soft skinned, red fruits with lots of bunches. Leaves are a deep green that contrasts well with the light green immature fruit. A control Hoagland solution was used as the base nutrient solution and ammonium sulfate **(**$(NH_4)_2SO_4$) and calcium chloride dihydrate ($CaCl_2.2H_2O$) were used for modified Hoagland solution to maintain nitrogen and calcium respectively.

2.3 Experimental Design

The experiment was conducted using a completely randomized design (CRD), with seven biological replicates per treatment, resulting in a total of 21 plants. Three treatments were defined in this study, with one control treatment: Treatment 1 (T1) served as the control and received nitrogen entirely in the nitrate form (100% NO_3^-: 0% NH_4^+). Treatment 2 (T2) received 50% nitrate and 50% ammonium, while Treatment 3 (T3) received 38% nitrate and 62% ammonium.

The different nitrogen ratios were achieved by partially replacing calcium nitrate with ammonium sulfate while maintaining a constant total nitrogen concentration. Replacing calcium nitrate also reduced the calcium supplied, calcium chloride

dihydrate ($CaCl_2.2H_2O$) was added to T2 and T3 to maintain equal calcium concentrations across all treatments. The addition of ammonium sulfate and calcium chloride dihydrate introduced sulfate (SO_4^{2-}) and chloride (Cl^-) ions into T2 and T3. The treatments were formulated to maintain the total nitrogen while varying the nitrate to ammonium ratio. However, the use of ammonium sulfate and calcium chloride dihydrate resulted in differences in sulfate and chloride supply among treatments. These additional ions also contributed to the higher electrical conductivity (EC) measured in T2 and T3.

The EC was 1.9-2.0 dS m^{-1} for T1 solution, 2.5-2.8 dS m^{-1} for T2 and 2.9-3.2 dS m^{-1} for T3. During the early vegetative stage distilled water 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. The pH of the nutrient solution was maintained between 5.8 and 6.5 throughout the experimental period.

2.4 Nutrient Solution Preparation

The nutrient solutions were prepared based on a modified Hoagland formulation from Kaur et al., 2016. Separate stock solutions were prepared for the macronutrients, micronutrients and iron chelate.

For the macronutrient stock solutions, 236.1 g of calcium nitrate tetrahydrate ($Ca(NO_3)_2 \cdot 4H_2O$), 101.1 g of potassium nitrate (KNO_3) 136.1 g of monopotassium phosphate (KH_2PO_4) and 246.5 g of magnesium sulphate heptahydrate ($MgSO_4 \cdot 7H_2O$) were each dissolved separately in distilled water and the volume was made up to one liter to make 1M stock solutions. The micronutrient stock solution was prepared by dissolving 2.8 g boric acid (H_3BO_3), 1.8 g manganese chloride tetrahydrate ($MnCl_2 \cdot 4H_2O$), 0.2 g zinc sulphate heptahydrate ($ZnSO_4 \cdot 7H_2O$), 0.1 g copper sulphate pentahydrate ($CuSO_4 \cdot 5H_2O$) and 0.025 g sodium molybdate ($Na_2MoO_4 \cdot 2H_2O$) in distilled water to obtain a final volume of one liter. Iron Chelate (Fe-EDTA) was prepared using 10.4 g Ethylene dia amine tetra acetic acid (EDTA. 2Na), 7.8 g Iron sulphate hepta hydrate (FeSO4.7H2O) and 56.1 g Potassium hydroxide (KOH) in distilled water to obtain a final volume of one liter.

2.4.1 Preparation of the Control Treatment (T1)

The control treatment (T1) supplied nitrogen entirely in the nitrate form (100% NO_3^-). One liter of the T1 working solution was prepared by adding 7.0 mL of calcium nitrate stock solution, 5.0 mL of potassium nitrate stock solution, 2.0 mL of monopotassium phosphate stock solution, 2.0 mL of magnesium sulfate stock solution, 1.0 mL of micronutrient stock solution and 1.0 mL of iron chelate stock

solution to distilled water. The final volume was made up to one liter. This treatment served as the reference nutrient solution.

Table 1: *Nutrient concentration (g/L) in Hoagland solution used as a control solution in the experiment and concentration of nutrients in (mL) used in the working solution in the treatment T1:100% NO_3^- according to Kaur et al., 2016*

Component		Amount in 1M solution (g / L)	Amount in 1L working solution (mL)
Calcium nitrate tetrahydrate	$Ca(NO_3)_2 \cdot 4H_2O$	236.1	7
Potassium nitrate	KNO_3	101.1	5
Monopotassium phosphate	KH_2PO_4	136.1	2
Magnesium sulphate heptahydrate	$MgSO_4 \cdot 7H_2O$	246.5	2
Micronutrients	H_3BO_3 $MnCl_2 \cdot 4H_2O$ $ZnSO_4 \cdot 7H_2O$ $CuSO_4 \cdot 5H_2O$ $Na_2MoO_4 \cdot 2H_2O$	Prepared separately*	1
Fe-EDTA	EDTA. 2Na FeSO4.7H2O KOH	Prepared separately*	1

**Micronutrients and Fe-EDTA stock solutions prepared separately according to the modified Hogland formulation as above*

2.4.2 Preparation of the Ammonium Containing Treatments (T2 and T3)

For T2 and T3, part of the calcium nitrate was replaced with ammonium sulfate ($(NH_4)_2SO_4$) to provide different proportions of nitrate and ammonium nitrogen while maintaining the total nitrogen concentration at 266 mg L^{-1}. Calcium chloride dihydrate ($CaCl_2 \cdot 2H_2O$) was added to compensate for the reduction in calcium because reducing calcium nitrate also reduced the calcium supplied by the nutrient solution.

Table 2: *Composition of the working nutrient solutions in (mL/L) targetting NO_3^-:NH_4^+ ratios in the three different treatments. T1= 100% NO_3^-: 0% NH_4^+ solution, T2 = 50% NO_3^-: 50% NH_4^+ solution and T3 = 38% NO_3^-: 62% NH_4^+ solution. The remaining components of the nutrient solution were maintained same volumes across three treatments.*

Treatment	NO_3^-: NH_4^+ratio	$Ca(NO_3)_2$ stock (mL L^{-1})	$(NH_4)_2SO_4$ stock (mL L^{-1})	$CaCl_2 \cdot 2H_2O$ (g L^{-1})
T1	100:0	7.00	0.00	0.00
T2	50:50	2.25	4.75	0.69
T3	38:62	1.11	5.89	0.86

A stock solution $(NH_4)_2SO_4$ was prepared at a concentration of 1M by dissolving 132.14 g of ammonium sulfate in distilled water and making the final volume up to one liter. The resulting stock solution was used to prepare T2 and T3 at application volumes of 4.75 and 5.89 mL L^{-1}, respectively.

The amounts of calcium nitrate, ammonium sulfate and calcium chloride used in the three treatments are summarized in Table 2. The remaining components of the nutrient solution, including potassium nitrate, monopotassium phosphate, magnesium sulfate, micronutrients and iron chelate, were maintained at the same volumes across all treatments.

2.5 Irrigation and Nutrient Application

Nutrient solution was applied twice per week beginning 18 days after transplanting. Each plant received 250 mL of modified Hoagland nutrient solution during each fertilizer application.

Irrigation with only water was continued manually according to crop growth stage, depending on the moisture condition of pumice substrate moisture and greenhouse temperature conditions. The pH and EC adjustment was monitored before application to ensure appropriate nutrient solution conditions as described above.

2.6 Data Collection

Plant growth and development, biomass production, yield and fruit quality parameters were evaluated throughout the experiment. Data were collected from all 21 plants in three treatments.

2.6.1 Plant Growth Analysis

Vegetative and reproductive parameters were recorded after transplanting. Vegetative parameters were collected by measuring the plant height and number of leaves of each plant. After the initiation of the flowering stage these measurements were repeated five times during the experimental period. The number of clusters, number of flowers, number of fruits, number of leaves and plant height were

recorded for each plant to evaluate treatments on vegetative growth. Vegetative and reproductive growth parameters were recorded from 6th week after transplanting (WAT), periodically at two week intervals. Vegetative growth characteristics included plant height and number of leaves per plant.

Reproductive parameters were collected after the flower initiation by measuring the number of clusters, number of flowers and number of fruits. At harvest (15th WAT), the number of fruits per plant, total fruit weights were recorded to determine yield performance. Following the final harvest, shoots and roots were separated to determine plant biomass and fresh weight of each component was recorded. Plant tissues were subsequently dried at a constant temperature for 72 hours for recording dry weight. After that, fresh and dry biomass were calculated for each treatment.

Chlorophyll measurements were measured before harvest (9th WAT) and after the completion of harvesting (15th WAT) using an MC-100 Chlorophyll Meter (Apogee Instruments, USA), which estimates the Chlorophyll Content Index (CCI) by measuring the absorbance of red and near infrared wavelengths transmitted through the leaf. Measurements were taken in triplicate from the fully expanded young mature leaf on each plant.

2.6.2 Fruit Quality Analysis

Fruit quality analysis was conducted using fully ripened, red tomato fruits collected from each treatment. Fruit quality was assessed by measuring total soluble solids (°Brix), titratable acidity and the sugar to acid ratio.

The °Brix (total soluble solids (TSS)) of three ripe tomatoes from each replicate was measured by using a Hanna HI96801 digital refractometer. The instrument determines the °Brix value by measuring the refractive index of aqueous solutions and includes automatic temperature control for accuracy. Before measurement, the refractometer was calibrated using distilled water according to the manufacturer's instructions. A drop of distilled water was placed on the surface and the device was adjusted to a 0.0 °Brix value. After calibration, the prism surface was dried with soft tissue paper. Approximately 2-3 drops of the filtered tomato juice were placed on the glass and the °Brix value was recorded, which was displayed on the digital screen. °Brix was measured using 3 fruits per replicate and the average °Brix value was calculated. Fruits were frozen (-20 °C) for further analysis. Sugar to acid ratios were calculated using Total Soluble Solids (TSS) and Titratable acididity (TA) ratios.

Titratable acidity (TA) of ripe fruits was determined using the standard acid based titration method. Six to eight fruits per plant from different clusters were selected for juice extraction to measure TA and pH. Chilled tomato samples were brought to room temperature before analysis. Each tomato was chopped thoroughly and the pulp was filtered to obtain homogenized juice sample from each replicate. pH measurements were recorded from each extracted juice sample using Hanna combo pH, EC and TDS digital meter. In total, 10 mL of the prepared juice sample was dissolved in 40 mL of distilled water, resulting in 50 mL sample. The resulting mixture was titrated with standard 0.1N sodium hydroxide (NaOH) solution. A digital pH meter was used to monitor the titration process and the endpoint was determined when the solution reached a pH value of 8.10 (Amr & Raie, 2022), which is considered the equivalence point for citric acid titration. The volume of NaOH consumed was recorded. Titratable acidity was expressed as percentage of citric acid and calculated using following formula (Vijay et al., 2010).

$$\text{Titratable Acidity (\%)} = \frac{(V_{NaOH} \times N_{NaOH} \times EW_{acid} \times 100)}{(V_{sample} \times 1000)}$$

Where:

V_{NaOH} = volume of NaOH used (mL)
N_{NaOH} = Normality of NaOH (0.1N)
EW_{acid} = Equivalent weight of the acid (64.04)
V_{sample} = Volume of sample (mL)

2.7 Statistical Analysis

A one way analysis of variance (ANOVA) was carried out with every parameter evaluated, to identify statistically significant differences among treatments, followed by a Tukey honestly significant difference (HSD) test at a 5% significant level ($p < 0.05$). Pearson's correlation analysis was performed to evaluate the relationship between the number of harvested fruits per plant and total soluble solids (TSS). Both statistical analysis and graphical representations were made in Minitab 22 and using Microsoft excel. Graphs and tables were prepared to illustrate differences among the treatments for plant growth, yield, chlorophyll content and fruit quality parameters.

3. Results

3.1 Vegetative and Reproductive Growth

The effects of the treatments on vegetative and reproductive development of tomato plants were evaluated using plant height, number of leaves, clusters, flowers and fruits. Treatment effects were assessed using one way ANOVA followed by Tukey's HSD test at the 5% significance level.

3.1.1 Vegetative Development

Vegetative development was evaluated based on leaf numbers and plant height (cm) recorded at different stages of plant development. During the 6th WAT, nitrogen treatment significantly affected plant height ($p < 0.001$). T3 recorded the highest mean plant height (6.9 ± 0.3 cm), followed by T2 (5.8 ± 0.2 cm) and T1 (5.5 ± 0.2 cm). Tukey's HSD test showed that T3 was significantly taller than T1 and T2, while T1 and T2 did not differ significantly (Table 3). On the 7th WAT, a similar treatment effect was observed ($p = 0.013$), with T3 recording the greatest plant height (7.9 ± 0.3 cm), significantly higher than T1 (6.7 ± 0.2 cm) and T2 (6.9 ± 0.2 cm) (Table 3).

Table 3: *Effect of different nitrate (NO_3^-) and ammonium (NH_4^+) ratios on plant height and leaf production of tomato plants measured from the 6th to the 15th WAT of plant development under greenhouse conditions. Values are presented as mean ± standard error (SE) of seven plants per treatment (n = 7). Different lowercase superscript letters within the same parameter indicate significant differences among treatments according to Tukey's HSD test at p < 0.05, T1 (0% NH_4^+), T2 (50% NH_4^+) and T3 (62% NH_4^+)*

		Vegetative Parameters		
WAT	**Parameter**	**T1**	**T2**	**T3**
6th	Plant height (cm)	5.5 ± 0.2^b	5.8 ± 0.2^b	6.9 ± 0.3^a
	Number of leaves	5.3 ± 0.2^a	4.9 ± 0.1^a	5.1 ± 0.1^a
7th	Plant height (cm)	6.7 ± 0.2^b	6.9 ± 0.2^b	7.9 ± 0.3^a
	Number of leaves	7.1 ± 0.1^a	6.7 ± 0.2^a	6.9 ± 0.3^a
9th	Plant height (cm)	9.0 ± 0.2^a	8.8 ± 0.2^a	9.4 ± 0.5^a
	Number of leaves	8.3 ± 0.2^a	7.9 ± 0.3^a	8.0 ± 0.4^a
11th	Plant height (cm)	11.6 ± 0.5^a	11.2 ± 0.6^a	11.3 ± 0.8^a
	Number of leaves	8.7 ± 0.3^a	8.0 ± 0.2^a	8.1 ± 0.3^a
13th	Plant height (cm)	12.4 ± 0.6^a	11.8 ± 0.6^a	11.8 ± 0.9^a
	Number of leaves	13.1 ± 0.5^a	8.7 ± 0.4^b	8.6 ± 0.3^b
15th	Plant height (cm)	13.4 ± 0.7^a	13.3 ± 0.8^a	12.8 ± 1.1^a
	Number of leaves	15.4 ± 0.5^a	9.9 ± 0.5^b	9.6 ± 0.4^b

From the 9th WAT onwards, plant height did not differ significantly among treatments. On the 9th WAT, mean plant height ranged from 8.8 ± 0.2 cm in T2 to 9.4 ± 0.5 cm in T3, with no significant treatment effect ($p = 0.427$). Similarly, no significant differences were observed at the 11th WAT ($p = 0.919$), 13th WAT ($p = 0.786$) or final measurement at the 15th WAT ($p = 0.862$). At the final measurement, T1 recorded the highest numerical plant height (13.4 ± 0.7 cm), followed by T2 (13.3 ± 0.8 cm) and T3 (12.8 ± 1.1 cm), but all treatments belonged to the same Tukey group (Table 3).

On the 6th WAT, the mean number of leaves ranged from 4.9 ± 0.1 in T2 to 5.3 ± 0.2 in T1, with no significant treatment effect ($p = 0.177$). Similarly, no significant differences were detected in the 7th, 9th or 11th WAT ($p = 0.334$, 0.568 and 0.202, respectively) (Table 3). A significant treatment effect on leaf production became evident at the 13th WAT ($p < 0.001$). T1 produced the highest number of leaves (13.1 ± 0.5), while T2 and T3 produced 8.7 ± 0.4 and 8.6 ± 0.3 leaves per plant, respectively. Tukey's HSD test showed that T1 differed significantly from both T2 and T3, while T2 and T3 were statistically similar. This difference was observed at the 15th WAT ($p < 0.001$), when T1 produced 15.4 ± 0.5 leaves per plant compared with 9.9 ± 0.5 and 9.6 ± 0.4 leaves in T2 and T3, respectively (Table 3). Overall, the vegetative growth results showed that T3 produced greater plant height during the early growth period, although T1 produced significantly more leaves during the later stages of development.

3.1.2 Reproductive Development

Reproductive development was evaluated based on clusters, flowers and fruits recorded at different stages of plant development. Treatment differences were limited during the initial reproductive stage but became more evident as reproductive development progressed.

During the 7th WAT, no significant differences were observed among treatments for either flower cluster number or flower number. Flower cluster number ranged from 2.6 ± 0.2 in T1 and T3 to 2.7 ± 0.2 in T2 ($p = 0.840$), while flower number ranged from 17.9 ± 1.5 in T3 to 19.0 ± 2.1 in T2 ($p = 0.941$) (Table 4).

During the 9th WAT, flower cluster number and fruit number were not significantly affected by nitrogen treatment ($p = 0.195$ and $p = 0.446$ respectively). Flower number also did not reach the 5% significance level ($p = 0.055$), although T3 recorded the highest numerical mean (33.4 ± 1.9 flowers per plant) (Table 4). At the 11th WAT, significant differences were observed in flower cluster number ($p = 0.002$) and flower number ($p = 0.036$). T1 produced significantly more clusters (8.3 ± 0.8) than T2 (5.3 ± 0.3) and T3 (5.4 ± 0.4). For flower number, T1 recorded

the highest mean (26.6 ± 5.9), while T2 recorded the lowest (12.1 ± 1.6). T3 (16.9 ± 1.8) was intermediate and did not differ significantly from either T1 or T2. In contrast, fruit number did not differ significantly among treatments at this stage (p = 0.059) (Table 4).

Table 4: *Plants were evaluated at the 7th, 9th, 11th, 13th and 15th measurement weeks to monitor reproductive development throughout the experimental period. The reproductive parameters included the number of flower clusters, number of flowers, number of fruits, and number of harvested fruits. Values are presented as mean ± standard error (SE) based on seven plants per treatment (n = 7). T1 (0% NH_4^+), T2 (50% NH_4^+) and T3 (62% NH_4^+)*

Reproductive Parameters				
WAT	**Parameter**	**T1**	**T2**	**T3**
7th	No. of clusters	2.6 ± 0.2[a]	2.7 ± 0.2[a]	2.6 ± 0.2[a]
	No. of flowers	18.3 ± 3.1[a]	19.0 ± 2.1[a]	17.9 ± 1.5[a]
9th	No. of clusters	5.0 ± 0.5[a]	4.0 ± 0.2[a]	4.4 ± 0.4[a]
	No. of flowers	31.4 ± 2.1[a]	26.6 ± 1.8[a]	33.4 ± 1.9[a]
	No. of fruits	8.6 ± 2.4[a]	10.4 ± 1.6[a]	7.0 ± 1.5[a]
11th	No. of clusters	8.3 ± 0.8[a]	5.3 ± 0.3[b]	5.4 ± 0.4[b]
	No. of flowers	26.6 ± 5.9[a]	12.1 ± 1.6[b]	16.9 ± 1.8[ab]
	No. of fruits	24.9 ± 1.4[a]	24.6 ± 1.6[a]	20.1 ± 1.3[a]
13th	No. of clusters	8.4 ± 0.8[a]	5.3 ± 0.3[b]	5.4 ± 0.4[b]
	No. of flowers	14.1 ± 1.1[a]	8.9 ± 1.2[b]	9.4 ± 0.9[b]
	No. of fruits	32.3 ± 1.1[a]	26.6 ± 1.3[b]	23.0 ± 0.9[b]
15th	No. of clusters	8.6 ± 0.8[a]	5.3 ± 0.3[b]	5.4 ± 0.4[b]
	No. of harvested fruits	41.4 ± 2.8[a]	30.3 ± 1.1[b]	27.4 ± 0.9[b]

Note*: Different lowercase superscript letters within the parameter indicate statistically significant differences among nitrogen treatments according to Tukey's honestly significant difference (HSD) test at $p < 0.05$. Values sharing the same superscript letter are not significantly different, although values with different letters differ significantly."No." denotes number*

On the 13th WAT, treatments significantly affected cluster number, flower number and fruit number (p = 0.001, 0.005 and < 0.001 respectively). T1 produced significantly more flower clusters (8.4 ± 0.8), flowers (14.1 ± 1.1) and fruits (32.3 ± 1.1) than both T2 and T3. T2 and T3 did not differ significantly from each other for any of these parameters (Table 4). At the final measurement, the number of clusters remained significantly different among treatments (p = 0.001). T1 produced the highest number of flower clusters (8.6 ± 0.8 per plant), while T2 and T3 produced 5.3 ± 0.3 and 5.4 ± 0.4 clusters per plant, respectively. Tukey's HSD test showed that T1 differed significantly from both T2 and T3, while T2 and T3 did not differ significantly (Table 4).

3.2 Yield Performance

Yield was evaluated based on the number of fruits per plant and total fresh fruit yield. The number of fruits produced per plant was significantly affected by the treatments ($p < 0.001$). Plants grown under the treatment without ammonium (T1) produced the largest number of fruits, with average of 41.4 ± 2.8 fruits per plant, while T2 and T3 produced 30.3 ± 1.1 and 27.4 ± 0.9 fruits per plant, respectively. Tukey's HSD test showed that T1 produced significantly more fruit than both T2 and T3, while no significant difference was observed between T2 and T3 (Table 4).

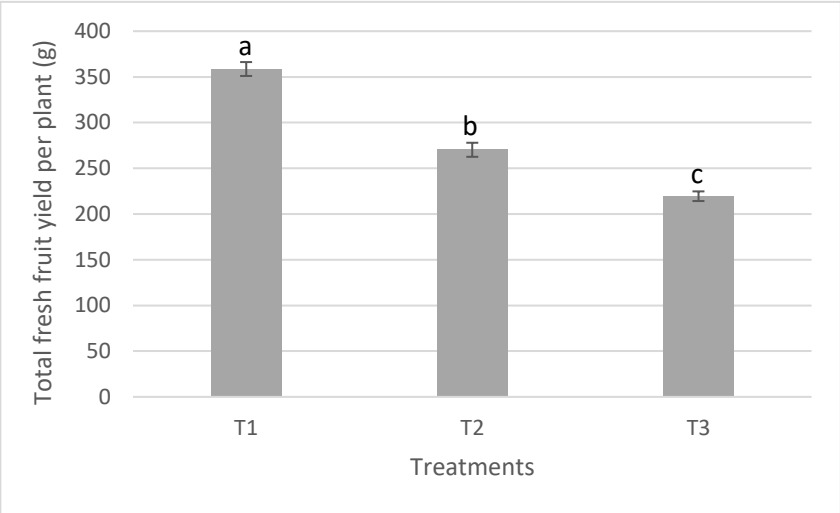


***Figure 1**: Total Fruit weight in (g) of tomato plants grown under different nitrate (NO_3^-) to ammonium (NH_4^+) ratios. Weight of tomato fruits were taken after harvest (15th WAT). Total fresh fruit yield per plant (g) was determined under three nitrogen treatments: with the x axis representing nitrogen treatments: T1 (0% NH_4^+), T2 (50% NH_4^+) and T3 (62% NH_4^+), while the y axis represents the total average fruit weight. Statistical differences among treatments were evaluated using Tukey's HSD test at $p < 0.05$.*

Total fresh fruit yield was significantly affected by the treatments ($p < 0.001$). The highest fruit yield was observed from the treatment without ammonium (T1), with an average total fruit weight per plant of 358.6 ± 7.6 g. The average fruit weighed T2 and T3 were 270.3 ± 7.7 g and 219.5 ± 5.3 g, respectively. Tukey's HSD multiple comparison test confirmed that all three treatments differed significantly from one another. The treatment without ammonium (T1) produced a significantly greater yield than T2 and T3, while T2 also produced a significantly greater yield than T3 (Figure 1).

3.3 Physiological Responses

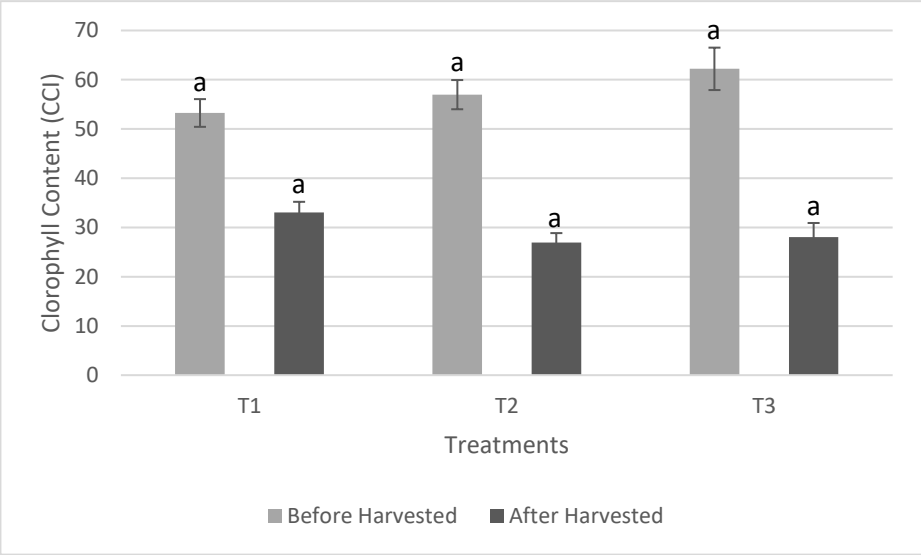


***Figure 2**: Chlorophyll content in leaves was measured under different nitrate (NO_3^-) to ammonium (NH_4^+) ratios before (9^{th} WAT) and after harvesting (15^{th} WAT). Average chlorophyll content (CCI units) was determined for plants grown under three nitrogen treatments, with the x axis representing nitrogen treatments: T1 (0% NH_4^+), T2 (50% NH_4^+) and T3 (62% NH_4^+), while the y axis represents chlorophyll content (CCI). Light color bars indicate chlorophyll content before harvesting and the dark bars represent chlorophyll content after harvesting and error bars represent the standard error of the mean (± SE). Statistical differences among treatments were analyzed using Tukey's HSD test at $p < 0.05$.*

The chlorophyll content measured before harvest ranged from 53.3 ± 2.8 in T1 to 62.2 ± 4.3 in T3. Although plants receiving the highest proportion of ammonium (T3) recorded the highest chlorophyll content, one way ANOVA indicated that there was no significant effect of treatment on chlorophyll content before harvest (p = 0.148) (Figure 2). In addition, Tukey's HSD test showed no significant differences among the three treatments.

After harvest, chlorophyll content declined in all treatments. The treatment without ammonium (T1) was recorded as the highest average chlorophyll content (33.1 ± 2.2), followed by T3 (28.1 ± 2.9) and T2 (26.9 ± 1.9) (Figure 2). However, the differences among treatments were not significant according to one way ANOVA (p = 0.166). Tukey's HSD test also indicated that chlorophyll content did not differ significantly among the treatments.

3.4 Biomass Production

Biomass production was evaluated by measuring fresh biomass and dry biomass at the end of the experiment to determine the effect of three treatments on overall plant growth.

Treatments had a significant effect on fresh biomass production ($p < 0.001$). Plants supplied with the treatment without ammonium (T1) produced the highest fresh biomass, with an average of 109.6 ± 4.2 g per plant, followed by T2 (75.4 ± 2.0 g per plant) and T3 (67.4 ± 0.7 g per plant) (Figure 3). Tukey's HSD test showed that fresh biomass in T1 was significantly greater than in T2 and T3, although no significant difference was observed between the two ammonium containing treatments.

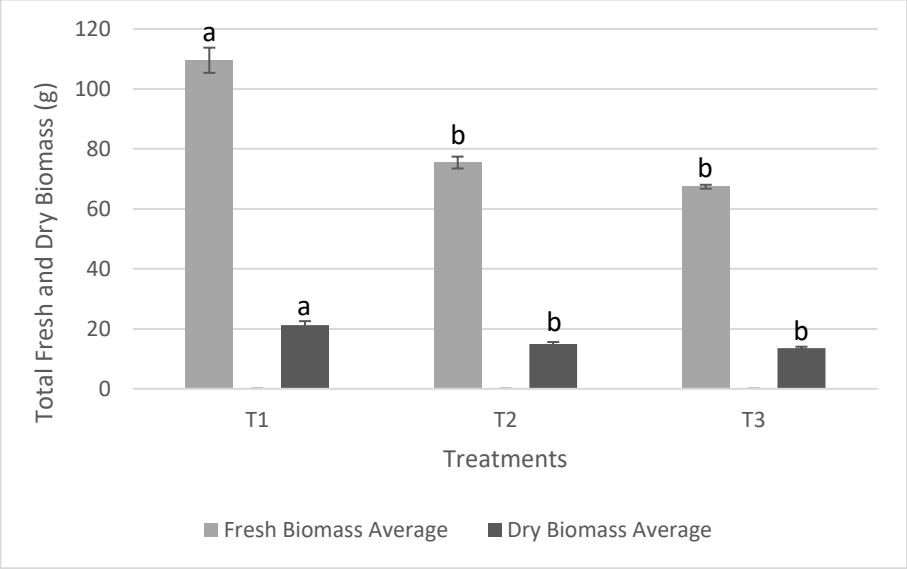


***Figure 3**: Biomass of plant grown under different nitrate (NO_3^-) to ammonium (NH_4^+) ratios. Fresh and Dry biomass were determined for plants grown under three nitrogen treatments, with the x axis representing nitrogen treatments: : T1 (0% NH_4^+), T2 (50% NH_4^+) and T3 (62% NH_4^+), while the y axis represents fresh and dry biomass (g) light color bars indicate average fresh biomass and the dark color bars represent average dry biomass and error bars represent the standard error of the mean (± SE). Statistical differences among treatments were analyzed using Tukey's HSD test at $p < 0.05$.*

Dry biomass was also significantly influenced by the treatments ($p < 0.001$). The treatment without ammonium (T1) produced the highest dry biomass, with an average of 21.3 ± 1.3 g per plant, while T2 and T3 recorded average dry biomass values of 14.9 ± 0.7 g and 13.6 ± 0.5 g per plant, respectively (Figure 3). Tukey's HSD test indicated that T1 produced significantly greater dry biomass than both T2 and T3, while no significant difference was detected between T2 and T3.

3.5 Fruit Quality

3.5.1 Fruit pH

The pH was significantly different among treatments ($p < 0.05$). Moderate ammonium treatment (T2) recorded the highest mean pH (4.47 ± 0.14), followed the treatment with the highest proportion of ammonium (T3) (4.34 ± 0.15), while the treatment without ammonium (T1) had the lowest mean pH (4.10 ± 0.02). According to Tukey's HSD test, T2 and T3 did not differ significantly from each other, whereas both treatments had significantly higher pH values than T1.

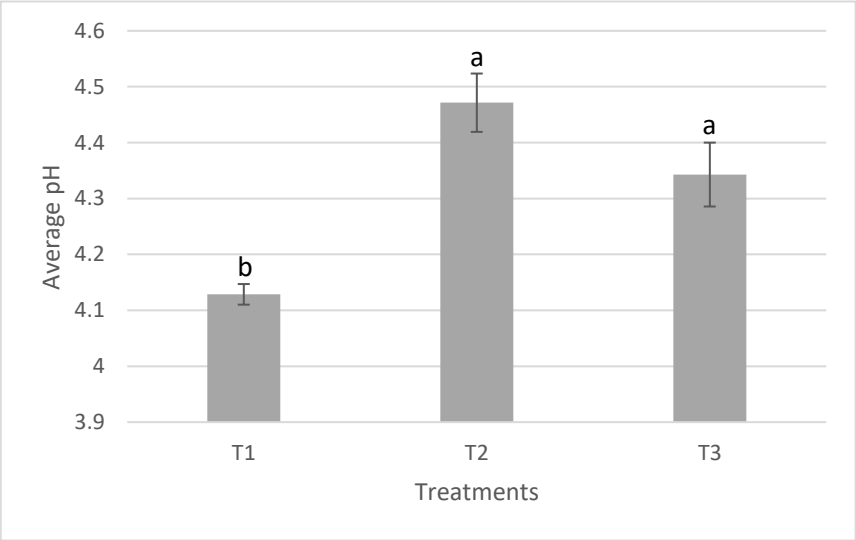


Figure 4: *Fruit pH was measured after harvest (15th WAT) under different nitrate (NO_3^-) to ammonium (NH_4^+) ratios treatments. Plants were grown under three nitrogen treatments, with the x axis representing nitrogen treatments: : T1 (0% NH_4^+), T2 (50% NH_4^+) and T3 (62% NH_4^+), while the y axis represents average pH. Bars indicate the mean pH values and error bars represent the standard error of the mean (± SE). Statistical differences among treatments were analyzed using Tukey's HSD test at $p < 0.05$.*

3.5.2 Total Soluble Solids (TSS)

The treatments significantly affected for total soluble solids ($p < 0.001$). Tomatoes produced under the treatment without ammonium (T1) were observed as having the lowest average TSS (5.71 ± 0.13 °Brix), while T2 recorded the highest value (6.67 ± 0.19 °Brix), followed by T3 (6.39 ± 0.19 °Brix) (Figure 5). Tukey's HSD test showed that T2 produced significantly higher TSS than T1, while T3 showed intermediate numerical values.

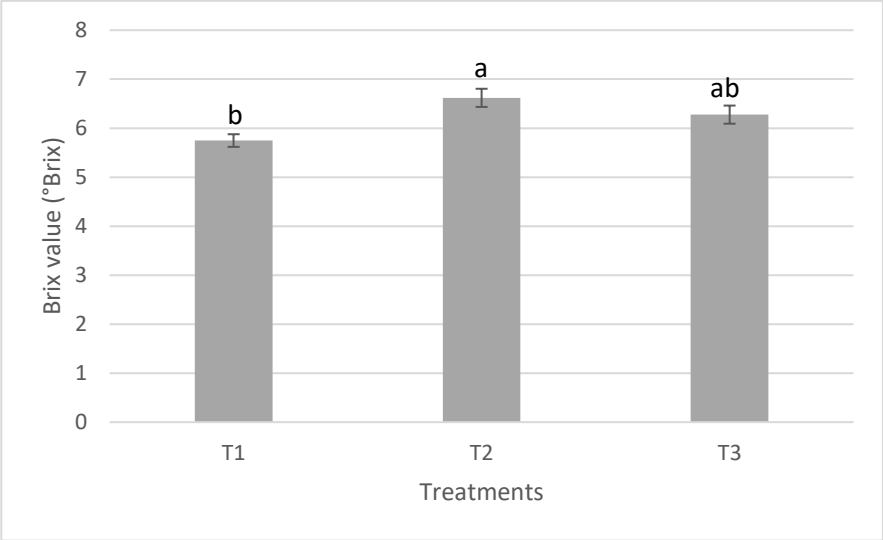


Figure 5*: Total Soluble Solids (TSS; °Brix) was measured after harvest (15th WAT) under different nitrate (NO_3^-) to ammonium (NH_4^+) ratio treatments. Plants were grown under three nitrogen treatments, with the x axis representing nitrogen treatments: T1 (0% NH_4^+), T2 (50% NH_4^+) and T3 (62% NH_4^+), while the y axis represents total soluble solids (°Brix) and error bars represent the standard error of the mean (± SE). Statistical differences among treatments were analyzed using Tukey's HSD test at $p < 0.05$.*

3.5.3 Titratable Acidity (TA)

Titratable acidity was significantly affected by the treatments ($p < 0.001$). The treatment without ammonium (T1) was recorded as the highest average titratable acidity (0.48 ± 0.01), followed by T3 (0.33 ± 0.02) and T2 (0.29 ± 0.01) (Figure 6). Tukey's HSD test indicated that all three treatments differed significantly from one another ($p < 0.05$).

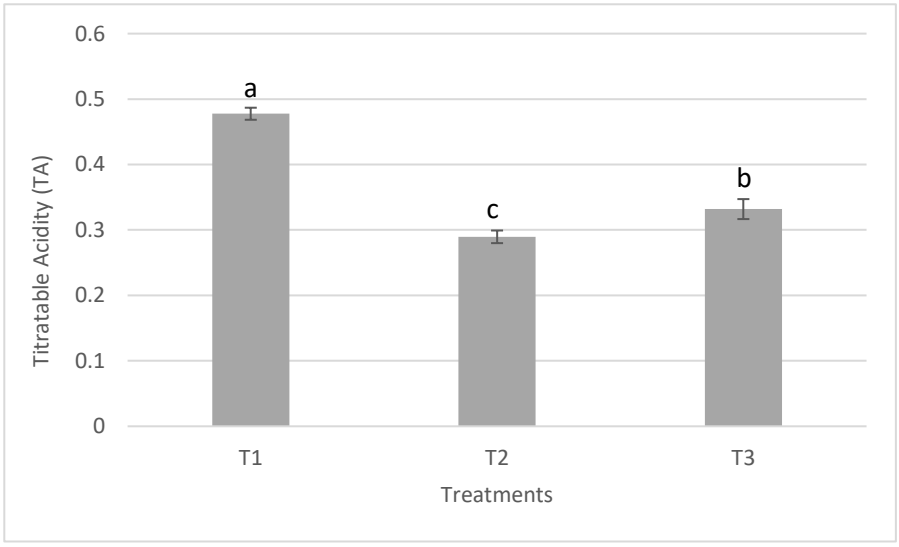


***Figure 6**: Titratable Acidity (TA) was measured after harvest (15th WAT) under different nitrate (NO_3^-) to ammonium (NH_4^+) ratios. Plants were grown under three nitrogen treatments, with the x axis representing nitrogen treatments: T1 (0% NH_4^+), T2 (50% NH_4^+) and T3 (62% NH_4^+), while the y axis represents titratable acidity (TA). Bars show the mean titratable acidity values and error bars represent the standard error of the mean (± SE). Statistical differences among treatments were evaluated using Tukey's HSD test at $p < 0.05$.*

3.5.4 Sugar to Acid Ratio

The sugar to acid ratio was significantly different among treatments ($p < 0.001$). Moderate ammonium treatment (T2) was observed as highest sugar to acid (23.00 ± 1.30), followed by T3 (19.46 ± 1.50) and T1 (11.96 ± 0.50) (Figure 7). Tomatoes produced under T2 had a significantly higher sugar to acid ratio than those produced under T1, while T3 had an intermediate sugar to acid ratio and did not differ significantly from T2, according to Tukey's HSD test, but differed significantly from T1. The higher sugar to acid ratio in T2 indicates a favorable sweetness to acidity balance based on the measured TSS and titratable acidity.

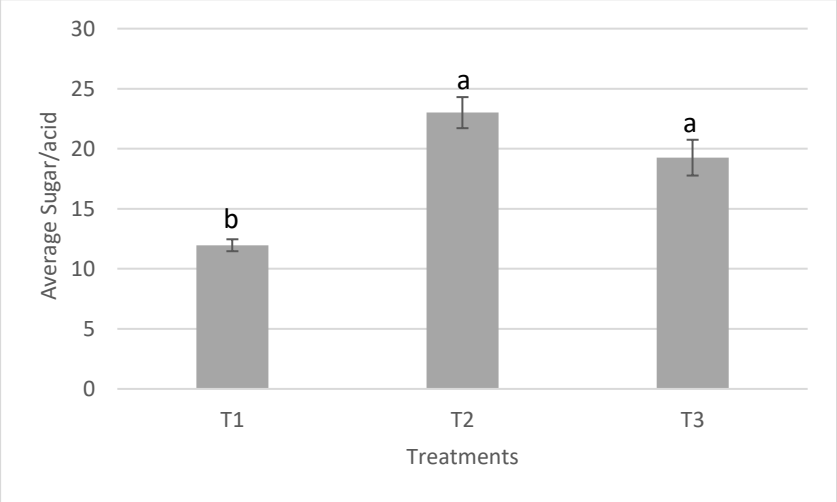


***Figure 7**: Sugar to acid ratio under different nitrate (NO_3^-) to ammonium (NH_4^+) ratios. Plants were grown under three nitrogen treatments, with the x axis representing nitrogen treatments: T1 (0% NH_4^+), T2 (50% NH_4^+) and T3 (62% NH_4^+), while the y axis represents sugar to acid ratio. Bars indicate the sugar to acid ratio values and error bars represent the standard error of the mean (± SE). Statistical differences among treatments were evaluated using Tukey's HSD test at $p < 0.05$*

3.5.5 Fruit Number vs Total Soluble Solids (TSS)

Fruit number per plant also varied among the treatments (Table 4). T1 produced the greatest number of harvested fruits per plant, while T2 and T3 produced fewer fruits. A Pearson correlation analysis conducted using data from all 21 plants showed a significant negative association between harvested fruit number and TSS ($r = -0.558$, $p = 0.008$), with fruit number explaining approximately 31.1% of the variation in TSS ($r^2 = 0.311$).

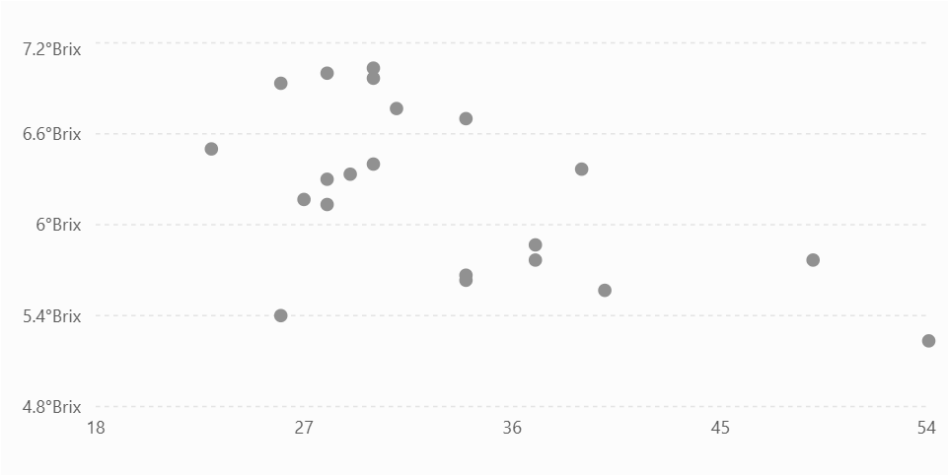


***Figure 8**: Relationship between the number of harvested fruits per plant and total soluble solids (TSS) of tomato fruits across the 21 experimental plants. The x axis represents the number of harvested fruits per plant, while the y axis represents the total soluble solids (TSS) content of tomato fruits. Each point represents an individual experimental plant. A significant negative association was observed between fruit number and TSS (Pearson's $r = -0.558$, $P = 0.008$, $r^2 = 0.311$)*

4. Discussion

Nitrogen form is an important factor affecting tomato growth because nitrate (NO_3^-) and ammonium (NH_4^+) differ in their uptake, assimilation and effects on plant metabolism. Nitrate is commonly associated with active shoot growth, while ammonium can be assimilated directly into amino acids but may become damaging when supplied at a high proportion. The response of tomato to NH_4^+ ratio is therefore dependent on the concentration of ammonium, cultivar and environmental conditions (Ben-Oliel et al., 2005).

The potential effect of the NO_3^-:NH_4^+ ratio on tomato performance is not expected to be uniform among all measured parameters because nitrate and ammonium influence nitrogen assimilation, carbon metabolism, ionic balance and nutrient uptake through different ways. Although NH_4^+ can be assimilated rapidly, a high proportion can increase the demand for carbon skeletons and disturb cellular pH and cation balance, while nitrate can additionally act as a signalling molecule regulating shoot development and carbon, nitrogen interactions (Britto & Kronzucker, 2006).

The results of the present study support this parameter dependent response. The treatment without ammonium (T1) produced greater leaf production at the later growth stages, more flower clusters and fruits, greater biomass and higher total fruit yield. In other hand, the 50% NO_3^-:50% NH_4^+ treatment (T2) was associated with higher TSS and sugar to acid ratio. Similar differences among growth and quality responses have been reported in tomato studies, showing that the response to nitrogen form depends on the parameter measured and the growing conditions (Heeb et al., 2005).

4.1 Vegetative and Reproductive Development

In the present study, the treatments included 100% NO_3^- : 0% NH_4^+ in T1, 50% NH_4^+ and 50% NO_3^- in T2 and 62% NH_4^+ and 38% NO_3^- in T3. The effect of the treatments on plant growth changed with plant development.

The greater early plant height in high ammonium treatment therefore may represent a short term advantage of readily assimilable ammonium rather than a sustained growth benefit. Once plant growth progressed, the higher NH_4^+ proportion may have increased the metabolic demand associated with ammonium assimilation. If carbon skeleton supply and ionic regulation become limiting, the initial benefit of direct NH_4^+ assimilation may not be maintained (Britto & Kronzucker, 2006).

This interpretation is supported by the pattern observed in the present results. Treatment with high proportion of ammonium (T3) was significantly taller than without ammonium (T1) and intermediate ammonium treatment (T2) during the 6th and 7th WAT, but this advantage disappeared from the 9th WAT onwards. Therefore, the higher proportion of NH_4^+ in high ammonium treatment affected early plant height but did not result in greater long term vegetative growth. Scientific studies showed that tomato growth responses to nitrate and ammonium depended on their relative proportion and environmental conditions, rather than increasing continuously with increasing NH_4^+. Similar study showed that 75% NO_3^-: 25% NH_4^+ ratio produced favourable growth and photosynthetic responses, showing that an intermediate nitrogen ratio can be more suitable than either treatment without ammonium or high ammonium treatment under their normal temperature conditions (Liu et al. 2017).

However, some studies represented that increasing ammonium supply can also disturb cellular pH regulation, carbon metabolism and ionic balance when ammonium assimilation exceeds the plant metabolic capacity (Britto & Kronzucker, 2006). Similar research studies showed that nitrate promoted stronger vegetative growth and enhanced physiological performance, while increasing ammonium reduced overall plant growth. Also, in different nitrogen forms, plant height was less responsive than other plant growth characteristics (Sun et al., 2023).

The present results partly agree with this interpretation because the early height response was not maintained and the treatments containing more NH_4^+ produced fewer leaves at the later stages. However, it cannot describe high ammonium treatment as showing ammonium toxicity because no direct measurements of ammonium toxicity, root injury or tissue NH_4^+ concentration were made. Furthermore, intermediate and high ammonium treatments differed from zero ammonium treatment in EC, sulfate and chloride supply. The results only show that the higher NH_4^+ treatment was associated with lower later leaf production, biomass and yield.

This difference is important because plant height alone did not represent the final growth response of the plants. Although high ammonium treatment was initially taller, the treatment without ammonium later produced significantly more leaves. The number of leaves increased from approximately 5 leaves per plant in each treatment at week 6 to approximately 15, 10 and 10 leaves per plant in treatment without ammonium, intermediate and high ammonium, respectively, at week 15. Therefore, the treatment effect became clearer as the plants developed. This suggests that the NO_3^-:NH_4^+ ratio had a greater effect on constant canopy development than on early stem extension.

The greater leaf production under treatment without ammonium is biologically relevant because leaf area determines the potential surface available for light interception and carbon assimilation. However, because leaf area and photosynthetic rate were not measured in this study, this should be considered a likely explanation rather than a direct measurement of the mechanism. Research on tomato has shown that nitrate to ammonium ratio can affect growth and photosynthetic processes, supporting the possibility that differences in nitrogen form can influence canopy development through several physiological processes rather than through plant height alone (Liu et al., 2017).

Nitrate has both nutritional and signalling functions and can regulate processes related to shoot development, cell division and carbon metabolism (Vidal & Gutiérrez, 2008). Therefore, the stronger later leaf production in without ammonium treatment is consistent with a greater ability of nitrate dominated nutrition to support continued shoot development. However, the result should not be interpreted as evidence that nitrate is always superior to ammonium. Some researchers found that ammonium dominated nutrition could produce similar red fruit yield to nitrate dominated nutrition under their experimental conditions (Heeb et al., 2005). This difference between studies indicates that the response depends on the exact nitrogen ratio, total nitrogen supply, cultivar and growing conditions.

The delayed appearance of significant treatment differences is important for understanding the effect of the NO_3^-:NH_4^+ ratio. The treatments did not strongly affect flowering during the earliest reproductive stage, but differences became clear as reproductive development progressed. This suggests that the effect of the nitrogen formulation was cumulative rather than an immediate effect on flower initiation. The greater leaf production that developed under treatment without ammonium may have increased the plant capacity to supply assimilates during the later reproductive period.

The results also show that the response was stronger for reproductive development than for early vegetative parameters. During 13th WAT, the treatment without ammonium had around 8 flower clusters and 32 fruits per plant, compared with 5 clusters and 26 fruits in intermediate ammonium treatment and 5 clusters and 23 fruits in high ammonium treatment. This pattern is consistent with the idea that sustained vegetative development can support later reproductive growth. In tomato, fruit production depends on the balance between the photosynthetic source and reproductive sinks; therefore, differences in canopy development can affect the plant capacity to support flowers and developing fruits (Prudent et al., 2009).

The lower reproductive development in intermediate and high ammonium treatments may also be related to the physiological effects of ammonium nutrition. High NH_4^+ supply can affect the uptake and balance of other cations and can increase the demand for carbon compounds needed for ammonium assimilation (Britto & Kronzucker, 2006). However, because nutrient concentrations in plant tissues were not measured, the present study cannot determine whether changes in K^+, Ca^{2+} or Mg^{2+} uptake actually occurred. Therefore, changed nutrient balance should be considered a possible mechanism rather than a demonstrated cause.

The final measurement showed that the treatment without ammonium continued to produce significantly more flower clusters than intermediate and high ammonium treatments. The treatment without ammonium had approximately 9 clusters, while intermediate and high ammonium treatments had approximately 5 clusters per plant. The fact that intermediate and high ammonium treatments remained statistically similar is also important. Increasing NH_4^+ from 50% to 62% did not cause a further significant reduction in the number of flower clusters. This indicates that the response was not simply proportional to the percentage of NH_4^+ supplied. A similar conclusion can be drawn from the early plant height results and later biomass results, increasing ammonium did not produce a simple linear response across all parameters. Previous study reported that tomato responses to nitrate to ammonium ratio depended on the ratio itself and environmental temperature, supporting the idea that an optimum range rather than a more better nitrate or more worst ammonium can occur (Liu et al., 2017).

4.2 Yield Parameters

The yield results showed the treatment effect in the present experiment. The treatment without ammonium (T1) produced the highest number of harvested fruits and the highest total fruit weight. T1 produced approximately 41 fruits per plant, while intermediate ammonium treatment (T2) and high ammonium treatment (T3) produced 30 and 27 fruits per plant, respectively. T1 was significantly different from both ammonium containing treatments, while T2 and T3 were statistically similar.

Total fruit weight also differed significantly among all three treatments. The treatment without ammonium produced 358.6 ± 7.6 g per plant, intermediate ammonium treatment produced 270.3 ± 7.7 g, and high ammonium treatment produced 219.5 ± 5.3 g. In this case, all three treatments were significantly different from each other. These results indicate that the treatment without ammonium supported the highest tomato productivity under the conditions of the present experiment. The reduction in yield in intermediate and high ammonium treatments was associated with a lower number of flower clusters and fruits per plant.

The yield result is particularly important because it agrees with the pattern observed for leaf production, flower clusters and fruit number. The treatment without ammonium produced the greatest number of leaves at the final stage, more flower clusters during the later reproductive stages and finally more harvested fruits. Therefore, the yield response appears to be connected with the cumulative development of the plants rather than being an isolated response at harvest.

The total fruit weight followed the same treatment order: T1 > T2 > T3. Importantly, all three treatments were significantly different. This means that increasing the NH_4^+ proportion from 0% to 50% and then to 62% was associated with progressively lower total fruit production in this experiment. However, this pattern should not be interpreted as proof that NH_4^+ itself caused the yield reduction because the nutrient formulations also differed in associated nutrients. Previous research demonstrates no significant difference in red tomato yield between nitrate and ammonium dominated treatments (Heeb et al., 2005), while other studies have reported yield reductions under high ammonium supply.

A hydroponic tomato study found that fruit fresh yield was about 25% lower under ammonium nutrition than under nitrate nutrition, while supplying a 4:1 NO_3^-:NH_4^+ ratio increased yield compared with nitrate alone. This supports the present observation that the response to nitrogen form can depend on the proportion of ammonium supplied rather than simply on the presence or absence of NH_4^+ (Flores et al., 2003).

4.3 Chlorophyll Content

Chlorophyll content was not significantly affected by the nitrogen treatments. Before harvest, high ammonium treatment (T3) had the highest numerical value, with a Chlorophyll Content Index (CCI) of 62.2 ± 4.3, followed by intermediate ammonium (T2) with 57.0 ± 3.3 and the treatment without ammonium (T1) with 53.3 ± 2.8. However, the ANOVA showed no significant treatment effect (p = 0.148). Since nitrogen is a major component of chlorophyll, increased nitrogen availability can enhance leaf greenness (Taiz, et al., 2015). Previous studies have also shown that the photosynthetic rate of plants supplied with ammonium is higher than those provided with nitrate (Sun et al., 2023). However, present experiment was not measured photosynthetic rate. After harvest, CCI decreased in all treatments. The treatment without ammonium had the highest numerical value at 33.1 ± 2.2, followed by high ammonium treatment at 28.1 ± 2.9 and intermediate ammonium treatment at 26.9 ± 1.9. However, the differences were again not significant (p = 0.166).

The absence of a significant treatment effect is important because it shows that the strong differences in biomass and yield were not accompanied by significant differences in measured chlorophyll content. In other hands, the nitrogen formulation affected plant productivity without producing a statistically detectable change in CCI. This result is biologically reasonable because chlorophyll content is only one part of photosynthetic capacity, it does not directly measure total leaf area, photosynthetic rate, carbon allocation or reproductive sink activity.

The numerical pattern also illustrates this point clearly. High ammonium treatment had the highest CCI before harvest, but it produced the lowest biomass and yield. Therefore, higher chlorophyll content did not result in higher productivity in this experiment. Previous study found that nitrate and ammonium ratio could affect tomato growth and photosynthesis, while the response of chlorophyll concentration depended on the experimental conditions (Liu et al., 2017). Their findings support the interpretation that chlorophyll concentration and whole plant productivity do not necessarily respond in the same way to nitrogen form.

After harvest, CCI decreased in all treatments. The decrease in CCI after harvest occurred in all three treatments, and the treatment differences remained non significant. Therefore, the decline is more reasonably interpreted as a developmental change associated with leaf ageing and senescence rather than a specific effect of the NO_3^-:NH_4^+ ratio. Chlorophyll degradation during senescence is a normal process that allows nutrients to be remobilized from older leaves to other plant organs (Hörtensteiner, 2006). Therefore, the CCI results do not provide evidence that one nitrogen ratio improved chlorophyll status more than another. Instead, they show that the main treatment differences in this experiment were expressed more clearly through leaf production, reproductive development, biomass and yield.

4.4 Biomass Production

Fresh and dry biomass showed a similar response to yield. The treatment without ammonium (T1) produced the highest fresh biomass, with 109.6 ± 4.2 g per plant, followed by intermediate ammonium treatment (T2) with 75.4 ± 2.0 g and high ammonium treatment (T3) with 67.4 ± 0.7 g. T1 was significantly higher than both T2 and T3, while T2 and T3 were not significantly different.

Dry biomass followed the same pattern. The treatment without ammonium produced 21.3 ± 1.3 g per plant, while intermediate and high ammonium treatments produced 14.9 ± 0.7 and 13.6 ± 0.5 g, respectively. The treatment without ammonium was significantly higher than both ammonium treatments, while

intermediate and high ammonium treatment did not differ significantly. The higher biomass production under zero ammonium treatment consists of its greater leaf number, flower cluster production and fruit number. Vegetative biomass provides the photosynthetic capacity required for reproductive development and greater canopy development can therefore contribute to greater total biomass and yield.

The lower biomass under intermediate and high ammonium treatments may be associated with the physiological effects of higher ammonium supply. Previous studies showed that the greater biomass under nitrate nutrition reflected better leaf development, photosynthesis and nutrient uptake (Marschner, 2012). Lower biomass in intermediate and high ammonium treatments may be suggests that high ammonium reduced plant growth through nutrient imbalance and reduced root function (Britto & Kronzucker, 2006).

The greater fresh and dry biomass in treatment without ammonium is consistent with its greater leaf production and reproductive development. Dry biomass is particularly useful because it represents accumulated plant material rather than water content. Therefore, the significantly greater dry biomass in treatment without ammonium provides stronger evidence that nitrate dominated nutrition supported greater overall plant growth under the conditions of this experiment.

The lower biomass in intermediate and high ammonium treatments may be related to the greater proportion of ammonium in these nutrient formulations. Ammonium assimilation is rapid, but it requires carbon skeletons and can affect ionic balance when the ammonium supply is high (Britto & Kronzucker, 2006). However, because tissue nutrient concentrations and root growth were not measured, the present study cannot determine whether the lower biomass was caused by ammonium metabolism, nutrient imbalance or another difference between the nutrient formulations.

4.5 Total Soluble Solids (TSS)

Total Soluble Solid (°Brix) was highest in intermediate ammonium treatment (T2) (6.67 ± 0.19 °Brix), followed by high ammonium treatment (T3) (6.39 ± 0.19 °Brix) and the treatment without ammonium (T1) (5.71 ± 0.13 °Brix). This shows that moderate ammonium supplies improved fruit sweetness with increased soluble solids. However, increasing ammonium over the moderate level did not further improve °Brix, suggesting that excessive ammonium limited its benefits. The treatment without ammonium produced the highest yield but the lowest °Brix. These findings suggest that a balanced nitrate to ammonium ratio promoted greater sugar accumulation in tomato fruits, while excessive ammonium did not provide additional improvements in fruit quality. Also, studies have shown increase in fruit

yield which was associated with a decreasing in sugar content and sweet flavor (Prudent et al., 2009).

Previous studies showed that mixed nitrogen forms increased soluble solids, soluble sugars and overall fruit quality compared with nitrate or ammonium supplied alone treatments. They also demonstrated that nitrogen form affects carbohydrate metabolism and the accumulation of flavor related compounds in tomato fruits (Wang et al., 2024). Further, previous study has been reported that ammonium dominated nutrition could support tomato production and improve some fruit taste characteristics (Heeb et al., 2005).

The individual plant data showed a significant negative association between harvested fruit number and TSS across all 21 plants (Pearson's ($r = -0.558$, $p = 0.008$, $r^2 = 0.311$). Therefore, plants carrying more harvested fruits tended to have lower TSS. This relationship is biologically feasible because a greater number of developing fruits increases competition among reproductive sinks for available assimilates. Previous study has also described an inverse relationship between increased tomato productivity and sugar or flavour concentration (Prudent et al., 2009).

4.6 Titratable acidity (TA)

Titratable acidity was also significantly affected by the treatments. The treatment without ammonium (T1) recorded the highest value of 0.48 ± 0.01, followed by high ammonium treatment (T3) at 0.33 ± 0.02 and intermediate ammonium treatment (T2) at 0.29 ± 0.01. Tukey test indicated that all three treatments differed significantly from one another. The lower titratable acidity in the ammonium treatments indicates that the nitrogen treatments affected the acid composition of the fruits. This is including with previous research showing that nitrogen form can affect tomato acidity and flavour. They also reported differences in taste and acidity between nitrate dominated and ammonium dominated tomato nutrition (Heeb et al. 2005).

The lower acidity observed under intermediate and high ammonium treatments may be related to changes in carbon metabolism and the allocation of assimilates during fruit development. Organic acids are important components of tomato flavour and changes in their concentration can influence the balance between sweetness and acidity. The present results therefore suggest that changing the NO_3^-:NH_4^+ ratio affected the acid balance of the fruit. However, the mechanism cannot be identified directly because individual organic acids were not analysed.

4.7 Sugar and Acid Ratio

The sugar to acid ratio was significantly different among the treatments. The intermediate ammonium treatment (T2) recorded the highest value of 23.00 ± 1.30, followed by high ammonium treatment (T3) at 19.46 ± 1.50, while the treatment without ammonium treatment (T1) had the lowest value of 11.96 ± 0.50. Intermediate ammonium treatment was significantly higher than the treatment without ammonium. The high sugar to acid ratio in intermediate ammonium treatment was mainly due to the combination of higher TSS and lower titratable acidity. This indicates that intermediate ammonium treatment had the most favorable balance between soluble solids and acidity among the treatments.

Previous research supports the importance of nitrogen management in tomato flavour. Previous study found that ammonium dominated nutrition improved sensory sweetness, acidity and overall flavour compared with nitrate dominated nutrition (Heeb et al., 2005). However, the sugar to acid ratio should not be interpreted as direct evidence of sensory sweetness because no sensory evaluation was conducted in the present study. Similarly, TSS does not represent sugars alone because it includes other soluble compounds. Therefore, the most appropriate interpretation is that intermediate ammonium treatment showed a more favorable sweetness to acidity balance based on the measured TSS and titratable acidity in this study.

4.8 Symptoms Observed in Plants During the Experimental Period

During the 7th WAT, some plant leaves showed wilting and drooping. However, this symptom was overcome through daily application of water at this period.

During the 9th WAT, purple to violet leaf discoloration was observed in all treatments, following flower initiation. Similar symptoms were observed across all treatments and did not progressively increase. Such discoloration is commonly associated with phosphorus deficiency or restricted phosphorus availability, particularly under conditions that reduce nutrient uptake (Savvas et al., 2018). In the present study, the irrigation water temperature was approximately 14 - 15 °C, which may have contributed to reduced phosphorus availability.

Because the symptoms occurred similarly across all treatments, they could not be clearly associated with the different NO_3^-: NH_4^+ ratios. However, phosphorus deficiency cannot be confirmed because leaf tissue phosphorus concentration and

root zone temperature were not measured. The irrigation time was later changed to reduce the possible influence of cool irrigation water.

4.9 Importance of NO_3^-: NH_4^+ Management in Horticulture

The potential importance of management for horticulture is related to the possibility of adjusting plant nutrition according to the desired production objective. In greenhouse and soilless tomato production, nutrient solutions can be accurately formulated and supplied through fertigation, allowing the relative proportion of nitrate and ammonium to be manipulated. This provides an opportunity to investigate nitrogen management not only for maximizing yield but also for improving selected fruit quality characteristics.

The present study demonstrates that the treatment without ammonium resulted the highest yield and biomass, while intermediate ammonium treatment resulted the highest TSS and sugar to acid ratio. Therefore, a nitrate dominated nutrient solution may be advantageous when maximum productivity is the primary objective, while an appropriate nitrate and ammonium ratio may provide benefits when fruit quality is given greater importance. The practical objective should therefore not be to maximize ammonium supply, but to identify a suitable ratio that provides an acceptable balance between yield and fruit quality.

The results show that adjusting the NO_3^-:NH_4^+ ratio can help achieve different production objectives. The treatment without ammonium was clearly more favourable for vegetative development, reproductive development, biomass and yield, whereas intermediate ammonium treatment was more favourable for TSS, fruit pH and sugar to acid ratio. Therefore, the choice of nitrogen ratio should depend on whether the main objective is maximum production, fruit quality improvement or a balance between the two.

Importantly, the present results do not indicate that increasing NH_4^+ is always beneficial for fruit quality. Intermediate ammonium treatment performed better than high ammonium treatment for TSS and sugar to acid ratio, even though high ammonium treatment contained more NH_4^+. This suggests that a moderate NH_4^+ proportion may be more suitable than a high proportion under the conditions of this experiment. Other tomato studies have also shown that the optimum nitrogen ratio depends on the growing environment and the parameter being evaluated (Liu et al., 2017).

4.10 Ammonium Nutrition as a Strategy for Fruit Quality Improvement

Previous studies have investigated the use of ammonium nutrition as a potential strategy for modifying tomato fruit quality. They reported that ammonium dominated mineral nutrition influenced tomato sensory characteristics, including sweetness, acidity, flavour and overall acceptance. This showed that nitrogen form can affect commercially relevant quality characteristics in addition to plant growth and yield (Heeb et al., 2005). Similar study showed that different NO_3^-: NH_4^+ ratios affected soluble solids, soluble sugars, titratable acidity and other fruit quality characteristics (Wang et al., 2024). These studies indicate that the response to nitrogen form is not limited to a simple increase or decrease in plant growth but can extend to the composition and flavour related properties of harvested fruits.

The results of the present study are generally consistent with this concept. The treatment without ammonium produced the highest yield, whereas the 50%:50% NO_3^-: NH_4^+ treatment produced the highest TSS and sugar to acid ratio and the lowest titratable acidity. This difference suggests that nutrient solution management may provide an opportunity to shift the balance between productivity and fruit quality. However, the lack of a further increase in TSS under the 62% NH_4^+ treatment indicates that increasing ammonium proportion does not necessarily result in continuous improvement in fruit quality with this study conditions.

Overall, the present results demonstrate that the effect of NO_3^-:NH_4^+ ratio was parameter specific. The treatment without ammonium favoured sustained vegetative development, reproductive development, biomass accumulation and yield, while the 50% NO_3^-:50% NH_4^+ treatment favoured TSS and sugar to acid ratio. The absence of a significant CCI response indicates that nitrogen form effects on productivity were not primarily expressed through chlorophyll concentration. Similarly, the greater early plant height under high ammonium treatment did not translate into greater final productivity, and increasing NH_4^+ from 50% to 62% did not consistently produce an additional response.

Therefore, the present findings can not simply demonstrate that nitrate is beneficial and ammonium is detrimental. Rather, they show that nitrate dominated nutrition was more favourable for productivity under the conditions of this experiment, while moderate ammonium was associated with advantages in selected fruit quality characteristics. The most appropriate NO_3^-:NH_4^+ ratio may therefore depend on whether maximum yield, fruit quality or a balance between these objectives is prioritized.

4.11 Future Perspectives and Recommendations

Future studies should evaluate a wider range of NO_3^-: NH_4^+ ratios under fully balanced nutrient conditions to identify the ratio that provides the best compromise between yield and fruit quality. Intermediate ratios between those used in the present experiment would be particularly useful because the present results suggest that 50% NH_4^+ produced greater TSS and sugar to acid ratio, whereas increasing the proportion to 62% did not provide additional quality improvement.

Further studies should also include individual sugars, organic acids, vitamin C, lycopene, fruit firmness and sensory evaluation to provide a more comprehensive assessment of fruit quality. Measurements of leaf and fruit nutrient concentrations would help determine whether changes in calcium, sulfur, potassium or other nutrients contribute to the observed response. Monitoring root zone pH and EC throughout the production period would also improve understanding of the interaction between nitrogen form and the growing environment.

A stage specific nitrogen strategy could also be investigated, in which nitrate dominated nutrition is used during early plant establishment and an appropriate mixed NO_3^-: NH_4^+ ratio is introduced during fruit development. Such an approach could potentially combine the vegetative and yield advantages of nitrate nutrition with the fruit quality benefits associated with an appropriate ammonium proportion. However, this approach requires experimental validation before practical recommendation.

Overall, the present findings suggest that NO_3^-: NH_4^+ ratio has potential as a component of quality oriented nitrogen management in tomato. The results indicate that the highest yielding treatment was not the treatment with the highest measured fruit quality values. Therefore, future research should focus on identifying NO_3^-: NH_4^+ ratio that provides an appropriate balance between productivity, fruit composition, flavour related characteristics and nutrient use efficiency.

5. Conclusion

The three nutrient solution formulations affected tomato growth, yield and selected fruit quality traits. The treatment without ammonium (T1) produced the greatest biomass and fruit yield, while 50% ammonium treatment (T2) had the highest Total Soluble Solids (TSS) content and sugar to acid ratio. However, these responses cannot be attributed solely to NO_3^-: NH_4^+ratio because the treatments also differed in electrical conductivity (EC) and accompanying ion supply. The higher fruit number in treatment without ammonium may also have contributed to differences in TSS. Therefore, the treatments showed a trade off between productivity and selected fruit quality attributes. Further studies should maintain equal EC and balanced accompanying ions to isolate the effect of nitrogen form.

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References

Ali, M.Y., Sina, A.A.I., Khandker, S.S., Neesa, L., Tanvir, E.M., Kabir, A., Khalil, M.I. and Gan, S.H., 2020. Nutritional composition and bioactive compounds in tomatoes and their impact on human health and disease: A review. Foods, 10(1), p.45. DOI: 10.3390/foods10010045

Amr, A. and Raie, W., 2022. Tomato components and quality parameters. A review. *Jordan J. Agric. Sci*, *18*(3), pp.199-220. https://doi.org/10.35516/jjas.v18i3.444

Asp, H. and Bergstrand, K.J., 2024. Nutrient utilization and growth of tomato crops fertilized with solid anaerobic digestate. Scientia Horticulturae, 329, p.112986. DOI:10.1016/j.scienta.2024.112986

Ben-Oliel, G., Kant, S., Naim, M., Rabinowitch, H.D., Takeoka, G.R., Buttery, R.G. and Kafkafi, U., 2005. Effects of ammonium to nitrate ratio and salinity on yield and fruit quality of large and small tomato fruit hybrids. *Journal of Plant Nutrition*, *27*(10), pp.1795-1812. DOI: 10.1081/PLN-200026430

Britto, D.T. and Kronzucker, H.J., 2006. Plant nitrogen transport and its regulation in changing soil environments. *Journal of Crop Improvement*, *15*(2), pp.1-23. DOI:10.1300/J411v15n02_01

Collins, E.J., Bowyer, C., Tsouza, A. and Chopra, M., 2022. Tomatoes: An extensive review of the associated health impacts of tomatoes and factors that can affect their cultivation. *Biology*, *11*(2), p.239. https://doi.org/10.3390/biology11020239

Flores, P., Navarro, J., Carvajal, M., Cerdá, A. and Martínez, V., 2003. Tomato yield and quality as affected by nitrogen source and salinity. *Agronomie*, *23*(3), pp.249-256. DOI:10.1051/agro:2002088

Gutierrez, E.E.V., 2018. An overview of recent studies of tomato (Solanum lycopersicum spp) from a social, biochemical and genetic perspective on quality parameters. https://pub.epsilon.slu.se

Heeb, A., Lundegårdh, B., Ericsson, T. and Savage, G.P., 2005. Effects of nitrate-, ammonium-, and organic-nitrogen-based fertilizers on growth and yield of tomatoes. *Journal of Plant Nutrition and Soil Science*, *168*(1), pp.123-129. https://doi.org/10.1002/jpln.200420420

Hörtensteiner, S., 2006. Chlorophyll degradation during senescence. *Annu. Rev. Plant Biol.*, *57*(1), pp.55-77. DOI: 10.1146/annurev.arplant.57.032905.105212

Kaur, H., Sharda, R. and Sharma, P., 2016. Effect of Hoagland solution for growing tomato hydroponically in greenhouse. *HortFlora Res. Spectr*, *5*, pp.310-315. https://www.scribd.com/document/432235164/Effect-of-Hogland-Solution-for-Hydroponic-Tomato

Li, H., Liu, H., Gong, X., Li, S., Pang, J., Chen, Z. and Sun, J., 2021. Optimizing irrigation and nitrogen management strategy to trade off yield, crop water productivity, nitrogen use efficiency and fruit quality of greenhouse grown tomato. *Agricultural Water Management*, *245*, p.106570. DOI:10.1016/j.agwat.2020.106570

Li, W., Zhang, Y., Tang, Z., Wang, J., Wu, Y. and Yu, J., 2024. Balanced Fertilization Enhances the Nutritional Value and Flavor Profile of Tomato Fruits. *Foods*, *13*(22), p.3599. https://doi.org/10.3390/foods13223599

Liu, G., Du, Q. and Li, J., 2017. Interactive effects of nitrate-ammonium ratios and temperatures on growth, photosynthesis, and nitrogen metabolism of tomato seedlings. *Scientia Horticulturae*, *214*, pp.41-50. https://doi.org/10.1016/j.scienta.2016.09.006

Mancuso, T., De Cianni, R., Di Vita, G.A., Spada, E., Brun, F., Spadaro, D.C. and Zanchini, R., 2024. Understanding Italian consumers' perceptions of tomato agricultural innovation: Exploring the nexus between sustainability, health and consumer beliefs. *Journal of Cleaner Production*, *435*, p.140528. DOI:10.1016/j.jclepro.2023.140528

Marschner, P. (2012). Marschner's mineral nutrition of higher plants (3rd ed.). Academic Press, London DOI:10.1016/C2009-0-63043-9

Ohyama, T., 2010. Nitrogen as a major essential element of plants. *Nitrogen Assim. Plants*, *37*, pp.1-17. https://www.researchgate.net/publication/234135771_Nitrogen_as_a_major_essential_element_of_plants

Prudent, M., Causse, M., Génard, M., Tripodi, P., Grandillo, S. and Bertin, N., 2009. Genetic and physiological analysis of tomato fruit weight and composition: influence of carbon availability on QTL detection. *Journal of experimental botany*, *60*(3), pp.923-937. DOI: 10.1093/jxb/ern338

Savvas, D. and Gruda, N., 2018. Application of soilless culture technologies in the modern greenhouse industry—A review. *Eur. J. Hortic. Sci*, *83*(5), pp.280-293. DOI:10.17660/eJHS.2018/83.5.2

Sun, J., Jin, L., Li, R., Meng, X., Jin, N., Wang, S., Xu, Z., Liu, Z., Lyu, J. and Yu, J., 2023. Effects of different forms and proportions of nitrogen on the growth, photosynthetic characteristics, and carbon and nitrogen metabolism in tomato. *Plants*, *12*(24), p.4175. https://doi.org/10.3390/plants12244175

Taiz, L., Zeiger, E., Møller, I. and Murphy, A., 2015. Plant physiology and development 6th ed Sinauer Associates Sunderland. *MA, USA*. https://sirsyedcollege.ac.in/crm/public/uploads/download_image/H8aTDrHeKuTogISO7SE1r80gjP2dmU.pdf

Vardanian, I., Sargsyan, G., Martirosayn, G., Pahlevanyan, A., Tsereteli, I., Martorosyan, H., Khachatryan, L., Zurabyan, A. and Harutyunyan, Z., 2025. Lycopene in tomatoes: genetic regulation, agronomic practices, and environmental influence. *Functional Food Science-Online ISSN: 2767-3146*, *5*(4), pp.127-145. DOI: https://www.doi.org/10.31989/ffs.v5i4.1617

Vidal, E.A. and Gutiérrez, R.A., 2008. A systems view of nitrogen nutrient and metabolite responses in Arabidopsis. *Current opinion in plant biology*, *11*(5), pp.521-529. http://dx.doi.org/10.1016/j.pbi.2008.07.003

Vijay, P., Singh, A. and Pandey, R., 2010. Determination of titrable acidity (TA). Post-Harvest. Physiol. *Fruits Flowers*, *44*, pp.1-103. DOI:10.13140/RG.2.2.13335.50088

Wang, C., Wu, G., Wang, H., Wang, J., Yuan, M., Guo, X., Liu, C., Xing, S., Sun, Y. and Talpur, M.M.A., 2024. Optimizing tomato cultivation: Impact of ammonium–nitrate ratios on growth, nutrient uptake, and fertilizer utilization. *Sustainability*, *16*(13), p.5373. DOI:10.3390/su16135373

Wang, S., Qiang, Q., Xiang, L., Fernie, A.R. and Yang, J., 2023. Targeted approaches to improve tomato fruit taste. *Horticulture research*, *10*(1), p.uhac229. DOI: 10.1093/hr/uhac229

Yang, Z., Yan, H., Liu, H., Yang, L., Mi, G. and Wang, P., 2025. Enhancing crop nitrogen efficiency: The role of mixed nitrate and ammonium supply in plant growth and development. *Biology*, *14*(5), p.546. https://doi.org/10.3390/biology14050546

Popular Science Summary

What makes a tomato a good tomato? Is it the number of fruits a plant produces, or how sweet and tasty those fruits are? For tomato growers, both are important. Producing a large harvest is valuable, but consumers also want tomatoes with good flavour. This raises an interesting question: **can the way we feed a tomato plant change both the amount of fruit it produces and the quality of those fruits?**

One of the most important nutrients for a tomato plant is nitrogen. It helps the plant grow leaves, flowers and fruits. But nitrogen can be supplied in different forms, and the plant may respond differently depending on the form it receives. This study explored what happens when the balance between two forms of nitrogen, nitrate and ammonium, is changed.

The experiment was carried out in a greenhouse at SLU Alnarp in Sweden using Sweet Sturdy™ Jo F1 tomatoes. Twenty one plants were grown under the same greenhouse conditions and divided into three groups. One group received nitrate only, another received an equal mixture of nitrate and ammonium and the third received a higher amount of ammonium. The plants were followed throughout the growing season to see how they grew and how many tomatoes they produced. The harvested fruits were also examined for characteristics related to sweetness and flavour.

The results revealed an interesting difference. The plants receiving nitrate only produced the largest harvest**.** They produced about 41 tomatoes per plant**,** with a total fruit weight of about 359 grams per plant. They also produced more plant material and, later in the growing period, more leaves and flower clusters.

But here is where the story becomes more interesting**:** the plants producing the most tomatoes did not have the highest sweetness related measurements. Plants receiving an equal amount of nitrate and ammonium had the highest value. They also had the highest balance between sweetness and acidity. Giving the plants even more ammonium did not improve the results. Instead, the plants with the highest amount of ammonium produced the smallest harvest.

Why might a plant with fewer fruits have higher sweetness related values? A tomato plant has a limited amount of energy and resources. When it produces many fruits, these resources have to be shared among all the developing fruits. In this study, plants with more fruits tended to have lower sweetness related values. This may have contributed to the difference in fruit quality between the treatments.

The study therefore tells an important story about balance. The treatment that produced the most tomatoes was not the same treatment that produced the highest fruit quality measurements**.** Under the conditions of this experiment, nitrate only treatment supported greater plant growth and fruit production, while a moderate amount of ammonium was associated with some favourable fruit quality characteristics.

There is also an important limitation. The three nutrient treatments differed not only in the forms of nitrogen but also in salt concentration and some other nutrients. This means that the results cannot be explained by nitrogen form alone. More carefully controlled experiments are needed to understand the effects more clearly.

In the end, growing a good tomato is not simply about giving the plant more nutrients. It is about finding the right balance between plant growth, harvest and fruit quality. Sometimes, the plant that gives us the biggest basket of tomatoes is not the one that gives us the sweetest fruit.

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