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INFLUENCE OF NITROGEN-SULFUR BALANCE ON TOMATO PRODUCTIVITY AND QUALITY TRAITS IN SOILLESS CULTIVATION

Güney Akınoğlu ✉, Ahmet Korkmaz

Department of Soil Science and Plant Nutrition, Faculty of Agriculture, University of Ondokuz Mayıs, Samsun, Türkiye

ABSTRACT

Nitrogen (N) and sulfur (S) are crucial macronutrient elements for physiological and biochemical processes in tomato plants. However, synergistic effects of lowering N and increasing S application on tomato yield and quality have not been documented. The effect of four N/S balances: 50.00, 9.20, 4.66 and 2.92, prepared by varying the concentration of N and S, were evaluated in tomatoes grown in soilless medium (peat + perlite). The experiment was conducted in a completely randomized design with three replicates. The results of the study showed that the optimal N/S balance in the nutrient solution differed depending on the properties investigated. The N/S balance of 9.20 resulted in the highest overall fruit yield, average fruit weight, fruit size and diameter. Moreover, the N/S balances required in the nutrient solution for the highest lycopene content (7.69 mg 100 g^{-1} fresh weight) and vitamin C content (20.63 mg 100 g^{-1} fresh weight) in tomato fruits were 50.00 and 9.20, respectively. It was found that the N/S balance above or below 9.20 had negative effects on yield and yield components as well as on some biophysical quality characteristics of the fruit. However, the N/S balance had no influence on the number of fruits, the firmness and shape index and the pH value of the fruits. Therefore, lowering N and increasing S application to the balance of 9.20 would have great potential to enhance the synergistic effect on the productivity and quality of tomato cultivation.

Keywords: *Lycopersicon esculentum*, soilless culture, nitrogen to sulfur balance, nutrient concentration, yield, fruit quality

INTRODUCTION

Over a long period of time, there has been a concerted effort to address the challenges associated with soil-based farming, particularly in greenhouse environments. Issues such as soil-borne diseases, poor soil fertility, and high salt content have prompted the exploration of alternative cultivation methods. Soilless culture, including both hydroponic and substrate-based systems, has gained prominence as a solution to these challenges [Fussy and Papenbrock 2022]. In the coming years, it will be essential to produce sufficient food for a growing population while minimizing the use of natural resources per capita and reducing environmental impact, a goal that can be supported through sustainable farming practices like soilless culture [Cámara-Zapata et al. 2019].

Soilless culture is increasingly popular as an innovative and effective form of technology [Lucke et al. 2019]. The method of soilless cultivation involves growing plants without using soil as a rooting medium. It is widely used to improve the regulation of environmental conditions for growth and to avoid soil ambiguity [Tzortzakis et al. 2020]. The plants are grown in a substrate with a continual supply of nutrient solution, allowing for optimal mineral nutrition

✉ guney.akinoglu@omu.edu.tr

management [Lu et al. 2022]. Commercially, substrate culture has been used successfully for fruiting vegetables [Tüzel et al. 2019].

The tomato (*Lycopersicon esculentum* L.) from the *Solanaceae* family has become one of the most significant horticultural crops in the past fifty years [Panno et al. 2021]. In 2020, global production of tomatoes reached roughly 187 million metric tons, positioning it as one of the most extensively cultivated crops worldwide [Dasgan et al. 2024]. China leads tomato production with about 65 million metric tons, while India and Türkiye rank second and third, producing 20.5 million and 13.2 million metric tons, respectively [FAOSTAT 2020].

Tomato fruit contains many phytochemical compounds that can improve human health [Khan et al. 2021]. This fruit is an important dietary source of lycopene, potassium, calcium, iron, folic acid and vitamin C [Feng et al. 2020, Gonçalves et al. 2020, Wu et al. 2022].

Managing substrate fertility for tomato crops is essential for maintaining fruit yield and quality, as tomatoes are among the vegetables with the highest nutrient requirements [Du et al. 2017]. Different sources of individual nutrient elements can be used as fertilizers to meet the plant's need for particular elements [Souri and Dehnavard 2018]. Tomato production requires optimal fertilization [Frías-Moreno et al. 2020]. Nitrogen (N) is one of the most important nutrients needed for plant growth and development and often the most restrictive nutrient in tomato production [Cheng et al. 2021]. Since nitrogen is an essential component of proteins, enzymes and nucleic acids, it plays a crucial role in various physiological and metabolic processes. Nitrogen is also essential for maintaining the structural integrity of tomato plants [Albornoz 2016]. Sulfur (S) is a vital constituent of all forms of life, including plants [Narayan et al. 2023]. Sulfur is a constituent of the proteinaceous amino acids (including cysteine and methionine), vitamins (biotin and thiamine), chlorophyll, phytochelatins, coenzyme A, and S-adenosyl methionine [Nakai and Maruyama-Nakashita 2020, Narayan et al. 2023]. Sulfur affects various aspects of plant life, including growth, development, nutritional quality and disease resistance [Kopriva et al. 2019, Abdalla et al. 2020, Meschede et al. 2020]. Attaining optimal nutrient usage efficiency is a primary target for sustainable agricultural systems, both from an economic and environmental perspective [Çakmakçı et al. 2023]. Various variables influence the total efficiency of nutrient use, including the availability of water [Shewangizaw et al. 2024], genetic acquisitions [Peng et al. 2022], and the availability of other nutrients [Duncan et al. 2018]. The presence of N and S in the growing medium can affect nutrient uptake in plant tissues and the concentration of both nutrients [Sutradhar et al. 2017, Carciochi et al. 2019]. Sulfur and nitrogen are crucial for protein synthesis in plants, and their availability is closely interrelated [Zhou et al. 2024]. Furthermore, the S status of the plant has a potent influence on N metabolism, and the S requirement is closely related to N nutrition [Zenda et al. 2021].

In general, plant performance can only be maximized by the application of N if sufficient S is present. Similarly, the maximum response to the application of S can only occur if sufficient N is present. Thus, S deficiency can reduce the efficiency of N utilization, and a similar reaction is expected in the opposite direction, i.e., N deficiency affects the efficiency of S utilization [Jobe et al. 2019]. In plants, N is present in the form of protein, and S is a component of two essential amino acids, methionine and cysteine. The absence of these elements results in a reduction in the synthesis of these amino acids, and proteins comprising them are incapable of being formed. For this reason, the plant's metabolism can be altered depending on the N form together with the S when fertilizing [Marschner 2012]. Moreover, both N and S can have synergistic effects and influence fruit production, ripening, and quality to some extent [Marschner 2012]. Siueia et al. [2020] reported that the interaction between N and S rates positively influenced fruit firmness, soluble solids (SS), titratable acidity (TA), and the SS/TA ratio while negatively affecting vitamin C, lycopene, and beta-carotene levels. However, this interaction did not change the quality characteristics of tomatoes compared to recommended values. Additionally, pH was solely influenced by increasing N rates, reaching a maximum of 4.2, which achieved the desired acidity level.

A literature review found a lack of knowledge concerning the effects of the interaction between N and S in terms of nutrient balance and nutrient concentration. It is hypothesized that the effects of N and S are not only due to the respective concentration in the nutrient solution but also to the balance of the two macronutrients. In this context, the aim of the present study was to evaluate the influence of the N/S balance in the nutrient solution at different N and S concentrations on the yield and yield components, biophysical, organoleptic and nutraceutical quality characteristics of tomato grown in a soilless medium.

MATERIAL AND METHODS

Plant material and growth conditions. Tomato (*Lycopersicon esculentum* L. cv. Kardelen F1) was used as plant material. Seedlings were produced in a commercial nursery located in Antalya (Türkiye). The tomato seedlings, which were almost 10 cm tall and with their second set of leaves, were transplanted singly into pots on 7 July 2022. In the experiment, the growth medium was prepared by mixing peat and perlite at a ratio of 2:1 (v/v). Peat moss (Klasmann) is a moss that belongs to the genus of peat moss (Sphagnum) and has a high water-holding capacity and a pH value between 5.5 and 6.0. The expanded mineral perlite is an inert, salt-free substrate with a neutral pH and a high aeration capacity. A total of 1500 g of medium was placed in each 3 L pot having a diameter of 16.5 cm and a depth of 19.0 cm. Drainage holes were drilled into the bottom of the pots. The present experiment was conducted in a greenhouse at the Experimental Field of Ondokuz Mayıs University (41°21' N, 36°11' E), Samsun, Türkiye. The conditions in the greenhouse were as follows: temperature of 29 ±4 °C/22 ±2 °C (day/night), photoperiod of 12 h, and relative humidity of 55% ±5%. The greenhouse used in the experiment had a metal structure measuring 6.0 × 16.0 m (96 m² of total area), with a ceiling height of 4.5 m and an arched frame. It was covered with a transparent plastic film to prevent UV degradation and direct sunlight exposure to the plants.

Experimental design and N/S balance. The experiment was arranged in a completely randomized block design with a one-factor setup. Each treatment was replicated three times, resulting in a total of 12 pots. The concentrations of macro- and microelements in the nutrient solution for the tomato plants were applied according to the procedures described by Alpaslan et al. [1998]. The treatments in relation to the balance of nitrogen and sulfur and the concentration of macroelements in the nutrient solution applied to the substrate medium are given in Table 1. In all nutrient solutions with different N and S concentrations, the total cations ($NH_4^+ + K^+ + Ca^{+2} + Mg^{+2}$ = 13.5 me L^{-1}) and the total anions ($NO_3^- + H_2PO_4^- + SO_4^{-2}$ = 13.5 me L^{-1}) are in equilibrium. The N/S balance in the nutrient solution was calculated using the following equation:

$$\text{N/S balance} = \text{N concentration (meq L}^{-1}\text{) / S concentration (meq L}^{-1}\text{)}$$

The concentrations of microelements in four different nutrient solutions containing varying concentrations of N and S used in the experiment are the same and are given below.

Manganese chloride dihydrate ($MnCl_2 \cdot 2H_2O$), iron (Fe)-EDDHA [ethylenediamine-N,N′-bis(2-hydroxyphenylacetic acid)], boric acid (H_3BO_3), copper sulfate pentahydrate ($CuSO_4 \cdot 5H_2O$), zinc sulfate heptahydrate ($ZnSO_4 \cdot 7H_2O$), and ammonium molybdate tetrahydrate [$(NH_4)_6Mo_7O_{27} \cdot 4H_2O$] were used to prepare a micro-nutrient solution at 5 µM manganese (Mn), 40 µM iron (Fe), 30 µM boron (B), 0.75 µM copper (Cu), 4 µM zinc (Zn) and 0.5 µM molybdenum (Mo). The pH of the plant nutrient solutions was modified to 5.5 with 1.0 M KOH or H_2SO_4 solution. Analytical-grade reagents were used throughout the experiment.

The growing media were moistened with tap water before transplanting the tomato seedlings. Irrigation with the nutrient solution was initiated 3 days after transplanting and was provided every day, allowing a 20% ±5% leaching fraction. The supply of 150 mL of nutrient solution per day to each pot started at transplanting and was maintained until 14 August 2022. Subsequent to that specific date, a quantity of 300 mL of nutrient solution was provided daily to each pot until the completion of the harvesting process. The volumes of nutrient solution applied to tomato plants were determined based on plant growth observed in previous experiments [Korkmaz et al. 2018]. In the soilless culture system, additional daily irrigation with tap water was carried out alongside the nutrient solution. The substrate moisture dynamics were monitored daily using a gravimetric method. To compensate for water loss due to evapotranspiration, the plants were watered daily before sunset, based on the weight loss of the pots. Plants were harvested on 7 October 2022.

Table 1. Nitrogen (N) and sulfur (S) balance and concentration of macroelements in the nutrient solution

N/S balance meq L^{-1} / meq L^{-1}	N:S stoichiometry mM : mM	Macro-nutrient solution compositions	NO_3^-	$H_2PO_4^-$	SO_4^{-2}	NH_4^+	K^+	Ca^{+2}	Mg^{+2}
			mM						
50.00	$\mathbf{N_{12.5} : S_{0.125}}$	12.5 mM N	**12.00**	1.25	**0.125**	**0.5**	5.25	2.75	1.125
		1.25 mM KH_2PO_4	–	1.25	–	–	1.25	–	–
		2.75 mM $Ca(NO_3)_2{\cdot}4H_2O$	5.50	–	–	–	–	2.75	–
		0.50 mM NH_4NO_3	0.50	–	–	0.50	–	–	–
		4.00 mM KNO_3	4.00	–	–	–	4.00	–	–
		0.125 mM $MgSO_4{\cdot}7H_2O$	–	–	0.125	–	–	–	0.125
		1.00 mM $Mg(NO_3)_2$	2.00	–	–	–	–	–	1.00
9.20	$\mathbf{N_{11.5} : S_{0.625}}$	11.5 mM N	**11.00**	1.25	**0.625**	**0.5**	5.25	2.75	1.125
		1.25 mM KH_2PO_4	–	1.25	–	–	1.25	–	–
		2.75 mM $Ca(NO_3)_2{\cdot}4H_2O$	5.50	–	–	–	–	2.75	–
		0.50 mM NH_4NO_3	0.50	–	–	0.50	–	–	–
		4.00 mM KNO_3	4.00	–	–	–	4.00	–	–
		0.625 mM $MgSO_4{\cdot}7H_2O$	–	–	0.625	–		–	0.625
		0.50 mM $Mg(NO_3)_2$	1.00	–	–	–	–	–	0.50
4.66	$\mathbf{N_{10.5} : S_{1.125}}$	10.5 mM N	**10.00**	1.25	**1.125**	**0.5**	5.25	2.75	1.125
		1.25 mM KH_2PO_4	–	1.25	–	–	1.25	–	–
		2.75 mM $Ca(NO_3)_2{\cdot}4H_2O$	5.50	–	–	–	–	2.75	–
		0.50 mM NH_4NO_3	0.50	–	–	0.50	–	–	–
		4.00 mM KNO_3	4.00	–	–	–	4.00	–	–
		1.125 mM $MgSO_4{\cdot}7H_2O$	–	–	1.125	–	–	–	1.125
2.92	$\mathbf{N_{9.5} : S_{1.625}}$	9.5 mM N	**9.00**	1.25	**1.625**	**0.5**	5.25	2.75	1.125
		1.25 mM KH_2PO_4	–	1.25	–	–	1.25	–	–
		2.75 mM $Ca(NO_3)_2{\cdot}4H_2O$	5.50	–	–	–	–	2.75	–
		0.50 mM NH_4NO_3	0.50	–	–	0.50	–	–	–
		3.00 mM KNO_3	3.00	–	–		3.00	–	–
		0.5 mM K_2SO_4	–	–	0.50	–	1.00	–	–
		1.125 mM $MgSO_4{\cdot}7H_2O$	–	–	1.125	–	–	–	1.125

Measurement of fruit yield and physical characteristics. The fruit yield was measured in the lab using a sensitive scale (Precisa, XB-620M, Switzerland). The fruit yield was calculated for each plant based on the cumulative fruit weight and the number of fruits during the six pickings. The average fruit weight was then calculated.

The height and diameter of the intact fruits were measured using a digital caliper (ASIMETO, Series 307). A measurement of fruit weight was made from the blossom end to the top of the fruit, and the diameter was taken as the maximal diameter of the equatorial section. The fruit shape index was determined as the vertical diameter divided by the horizontal diameter. Every hour, the caliper was washed with water to remove deposited plant parts. A digital penetrometer (PCE Instruments, PCE-FM 200) with a cone-shaped probe of Φ8 mm was used for measuring firmness in the equatorial zone. The resistance at the penetration of the probe was measured and expressed in kg cm^{-2}.

Fruit sampling and quality analysis. Immediately after collection, fully ripened tomato fruits of each replicate were washed in tap water, dried with a paper towel and then cut in half. The seeds were discarded, and the pericarp and mesocarp were crushed to a homogeneous puree in a blender (Tefal, Type: MB450, Türkiye) for about 2 minutes. Part of the sample was instantly used for some analyses (fruit dry matter, titratable acidity, total soluble solids, lycopene, ascorbic acid, and nitrate). In addition, the squeezed juice was further filtered with a 120 mm Whatman paper filter. The clearly filtered juice was used for the pH analysis. pH was measured using a pH meter (Mettler Toledo Instruments, SevenCompact pH meter S220) [AOAC 1990].

The amount of dry matter (%) was determined gravimetrically by drying 5 g of tomato homogenate in a laboratory oven (Nüve, ES-500, Türkiye) set at 70 °C until a stable weight was attained. To determine the titratable acidity (TA), filtered tomato juice (10 mL) was titrated with 0.1 N standardized sodium hydroxide (NaOH) solution till equilibrium (pH of 8.1) and the measured TA was expressed as the concentration (%) of citric acid, a major organic acid in tomatoes. For the determination of total soluble solids (TSS), a single drop of the clear juice was measured using a digital refractometer Atago PAL-1 (3810), 0.0–53.0 Brix (Atago, Tokyo, Japan) and the measurement was represented in °Brix [AOAC 1990]. The method described by Fish et al. [2002] was used to determine the lycopene content in tomatoes. The vitamin C (ascorbic acid) content was determined by the titration method based on fresh weight (FW) described by Padayatt et al. [2001]. Nitrate was determined in fresh samples using the salicylic acid method [Cataldo et al. 1975].

Statistical analysis. Statistical analysis was performed using JMP version 5.1. Data were presented as means ±standard errors. A one-way analysis of variance (ANOVA) was conducted to assess overall treatment significance (p < 0.05). Pairwise comparisons among treatment means were performed using Fisher's Least Significant Difference (LSD).

RESULTS

Effect of the N/S balance on fruit productivity. The results of the effects of decreasing N or increasing S in the nutrient solution applied to substrate culture on the yield and its components of tomato are given in Fig. 1(A–C).

A reduction in the N concentration or an increase in the S concentration significantly affected (p < 0.05) total fruit yield. The highest total yield (1841.73 g plant^{-1}) was obtained at stoichiometry $N_{11.5}$: $S_{0.625}$ in the nutrient solution. The yield values obtained in other stoichiometric nutrient ratios were close to each other, and the difference between them was not statistically significant (Fig. 1A). The ideal N/S balance in the nutrient solution for the highest fruit yield was determined to be 9.20. When the N/S balance was

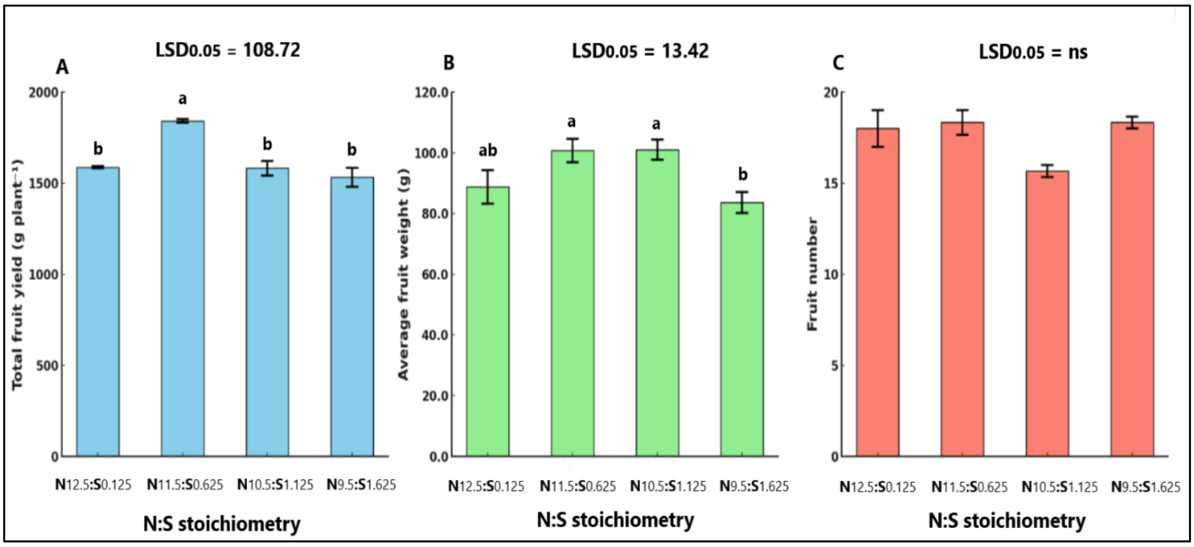

Fig. 1. Effect of nitrogen (N) and sulfur (S) concentration in the nutrient solution on the yield and yield components of tomato plants: (A) total fruit yield, (B) average fruit weight, (C) fruit number per plant. Values are presented as means ±SE. Distinct letters indicate statistically significant differences according to Fisher's least significant difference (LSD) test (p < 0.05); ns: non-significant.

Table 2. Effect of nitrogen (N) and sulfur (S) concentration in the nutrient solution on size, diameter, shape index, and firmness of tomato fruit cv. Kardelen F1

N:S stoichiometry	Fruit size (mm)	Fruit diameter (mm)	Fruit shape index	Fruit firmness (kg ·cm^{-2})
$N_{12.5}$:$S_{0.125}$	53.45 ±1.13 a	62.97 ±0.70 a	0.84 ±0.02	3.09 ±0.15
$N_{11.5}$:$S_{0.625}$	52.23 ±0.72 a	61.86 ±1.59 a	0.84 ±0.02	2.63 ±0.01
$N_{10.5}$:$S_{1.125}$	51.44 ±0.39 ab	59.23 ±1.41 ab	0.86 ±0.03	2.79 ±0.05
$N_{9.5}$:$S_{1.625}$	49.52 ±0.64 b	55.76 ±0.87 b	0.88 ±0.02	2.77 ±0.15
Level of significance	*	*	ns	ns
$LSD_{0.05}$	2.51	3.89	–	–

Each value represents mean ±SE (n = 3). There is no significant difference at 0.05 between the mean values given in the column with the same letters.
*significant at 5%; ns: non-significant

higher or lower than 9.2, a decrease in total fruit yield was observed. Increasing the N concentration from 11.5 to 12.5 mM and simultaneously reducing the S concentration in the nutrient solution from 0.625 to 0.125 mM reduced total fruit production by 32.63%. Compared to the treatment with an N/S balance of 9.20, the treatments with an N/S balance of 4.66 and 2.29 reduced the total fruit yield by 14.16% and 16.80%, respectively. A reduction in the N concentration or an increase in the S concentration significantly affected ($p < 0.05$) average fruit weight. The highest average fruit weight (101.00 g) was obtained at stoichiometry $N_{10.5}$:$S_{1.125}$ in nutrient solution. The average fruit weights were similar in the $N_{11.5}$:$S_{0.625}$ and $N_{10.5}$:$S_{1.125}$ treatments. An increase or decrease in the N/S balance in the nutrient solution led to a decrease in the average fruit weight. Moreover, the lowest fruit weight (83.64 g) was obtained when treated with $N_{9.5}$:$S_{1.625}$ (Fig. 1B). However, this change in the N:S ratio did not significantly affect the number of fruits per plant (Fig. 1C).

Effect of the N/S balance on biophysical quality characteristics of fruits. The N/S balance in the nutrient solution had a significant effect ($p < 0.05$) on fruit size and diameter. The largest fruit (53.45 mm) was obtained at stoichiometry $N_{12.5}$:$S_{0.125}$ in the nutrient solution. There was no difference between treatments $N_{12.5}$:$S_{0.125}$ and $N_{11.5}$:$S_{0.625}$ in terms of their effects on fruit size (Table 2). The fruit size of tomato plants grown in treatments with an N/S balance of 50.00 and 9.20 in the nutrient solution was found to be higher. Tomato grown in a treatment with a lower N/S ratio (2.92) than these N/S ratios showed a significant decrease in fruit size. The highest fruit diameter (62.97 mm) was obtained in the $N_{12.5}$:$S_{0.125}$ stoichiometry, but there was no difference between the $N_{12.5}$:$S_{0.125}$, $N_{11.5}$:$S_{0.625}$ and $N_{10.5}$:$S_{1.125}$ treatments in terms of fruit diameter (Table 2). Fruit diameter decreased significantly in the treatment with an N/S balance of 2.92 in the nutrient solution. However, this change in N:S stoichiometry did not significantly affect fruit shape index or fruit firmness (Table 2).

Effect of the N/S balance on physico-chemical quality characteristics of fruits. The results of the effects of decreasing N or increasing S in the nutrient solution applied to substrate culture on tomato physico-chemical quality traits are given in Fig. 2(A–D).

The reduction of N or the increase of S in the nutrient solution had no effect ($p > 0.05$) on the pH value of the tomato fruits (Fig. 2A). However, the N/S balance in the nutrient solution had a significant impact ($p < 0.05$) on the total soluble solids of the tomato fruit. The tomatoes cultivated in the nutrient solution with a N/S balance of 50.00 had the highest value (4.70 °Brix) in the fruit, while those grown in the solution with a N/S balance of 4.66 had the lowest value (4.16 °Brix) in the fruit. Increasing the S concentration from 0.125 to 1.125 mM and simultaneously reducing the N concentration in the solution of nutrients from 12.5 to 10.5 mM decreased the TSS of the tomato fruits (Fig. 2B).

The N/S balance in the nutrient solution had a significant effect ($p < 0.05$) on the titratable acidity of the tomato fruit. The increase of the N concentration from 11.5 to 12.5 mM and the simultaneous reduction of the S concentration in the nutrient solution from 0.625 to 0.125 mM reduced the TA of the tomato fruits (Fig. 2C).

The N/S balance in the nutrient solution had a significant effect ($p < 0.05$) on the dry matter content of the fruit. The maximum dry matter content (7.37%) of the tomato fruit was achieved with the stoichiometry $N_{12.5}$:$S_{0.125}$, while the stoichiometry $N_{11.5}$:$S_{0.625}$ resulted in the lowest dry matter content (6.77%). Nevertheless, the dry matter content of tomato fruit remained unaffected by the stoichiometry $N_{10.5}$:$S_{1.125}$ and $N_{9.5}$:$S_{1.625}$, as per the stoichiometry $N_{12.5}$:$S_{0.125}$ (Fig. 2D).

Effect of the N/S balance on nutraceutical quality characteristics of fruits. The results of the effects of

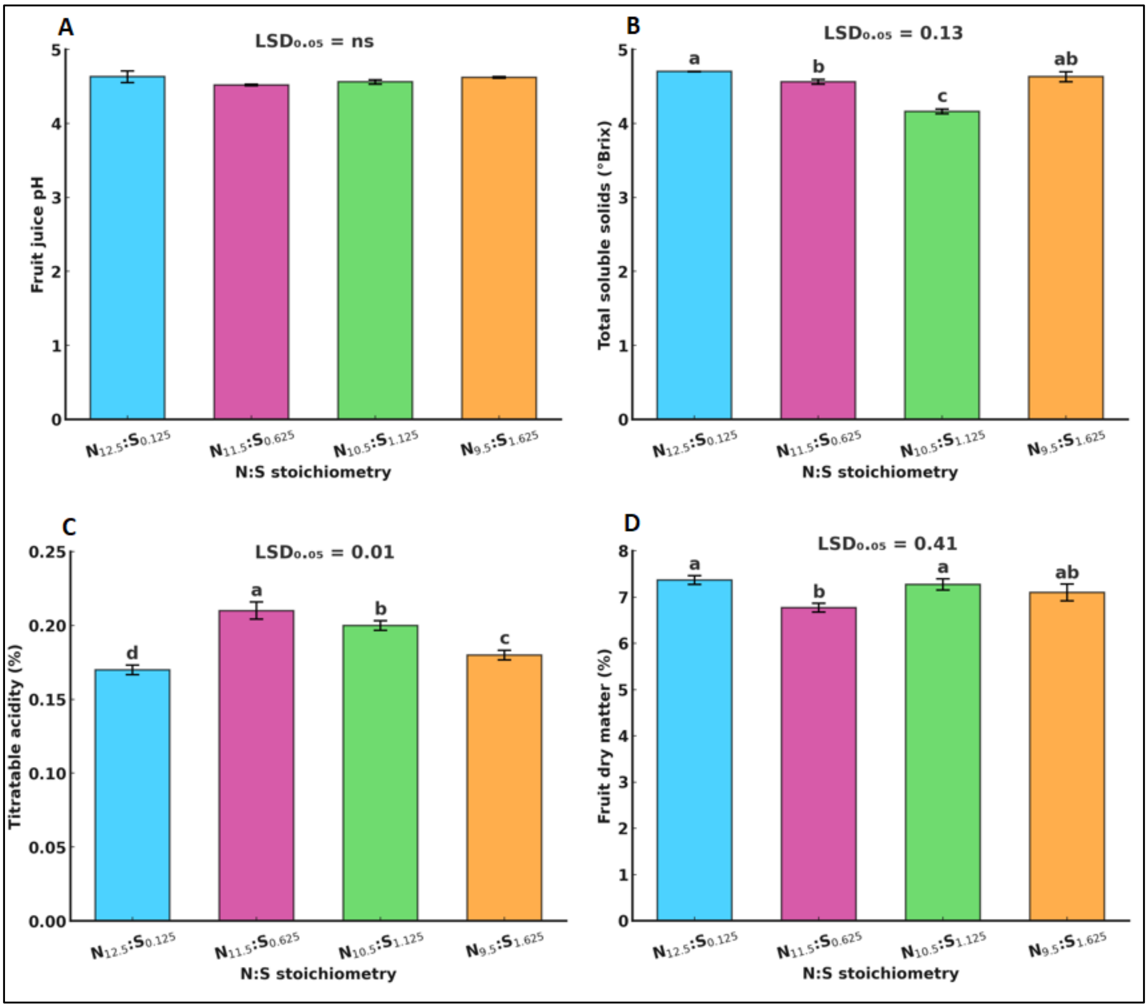

Fig. 2. Effects of nitrogen (N) and sulfur (S) concentration in the nutrient solution on the physico-chemical quality characteristics of tomato fruit: (A) pH, (B) total soluble solid, (C) titratable acid, (D) fruit dry matter (%). Values are presented as means ±SE. Distinct letters indicate statistically significant differences according to Fisher's least significant difference (LSD) test ($p < 0.05$)

decreasing N or increasing S in the nutrient solution applied to substrate culture on nutraceutical quality traits of tomato are given in Fig. 3(A–C).

The change in the N to S ratio had a substantial statistical influence ($p < 0.05$) on the lycopene content in tomato fruit. This carotenoid content in the fruit was the highest (7.69 mg 100 g^{-1} FW) in tomato plants grown in nutrient solution with N/S balance of 50.00, whereas it was the lowest (5.18 mg 100 g^{-1} FW) in tomato plants grown in the solution with a N/S balance of 2.92 (Fig. 3A). Increasing the S concentration from 0.125 to 1.625 mM and simultaneously reducing the N concentration in the nutrient solution from 12.5 to 9.5 mM reduced the lycopene content in tomato fruits by 32.63%.

The variation in N:S stoichiometry had a significant effect ($p < 0.05$) on the vitamin C content in tomato fruit. The tomatoes cultivated in the nutrient solution with a N/S balance of 9.20 had the highest vitamin C content (20.63 mg 100 g^{-1} FW), while those grown in the solution with a N/S balance of 50.00 had the lowest vitamin C content (13.16 mg 100 g^{-1} FW) (Fig. 3B). Increasing the N content from 11.5 to 12.5 mM and reducing the S content from 0.625 to 0.125 mM reduced the vitamin C content in tomato fruit by 36.20%. Similarly, elevating the S concentration in the nutrient solution from 0.625 to 1.125 mM and 1.625 mM and lowering the nitrogen concentration from 11.5 to 10.5 mM and 9.5 mM resulted in a decrease in the vitamin C content in the fruit by 32.81% and 21.95%, respectively.

The change in the N to S ratio had a substantial statistical influence ($p < 0.05$) on the nitrate (NO_3^-) content in tomato fruit. The tomatoes cultivated in the nutrient solution with a N/S balance of 50.00 had the highest NO_3^- content (13.75 mg·kg^{-1} FW), while those grown in the solution with a N/S balance of 2.92 had the lowest NO_3^- content (9.18 mg·kg^{-1} FW) (Fig. 3C). In other words, decreasing the N content from 12.5 to 9.5 mM and increasing the S content from 0.125 to 0.625 mM reduced the NO_3^- content in tomato fruit by 33.23%.

DISCUSSION

Plants exhibit higher nutrient efficiency when nutrients are supplied in a balanced way, as the nutrient uptake rates are determined by the concentration in the root zone and by the interrelation between nutrients, which is as critical as the total concentration of ions [Alvarado-Camarillo et al. 2018]. As essential mineral nutrients for proteins, amino acids, enzymes,

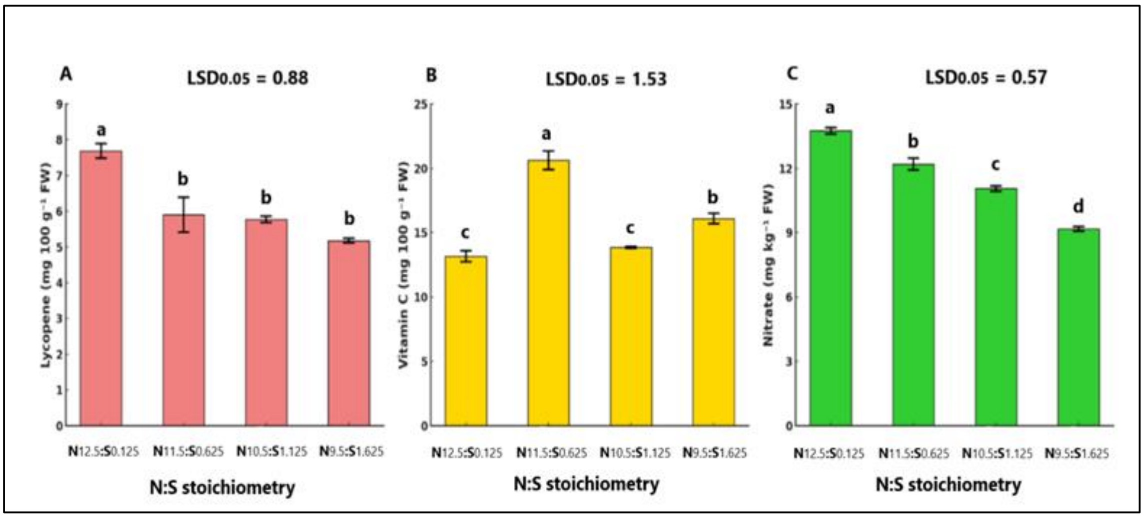

Fig. 3. Effects of nitrogen (N) and sulfur (S) concentration in the nutrient solution on the nutraceutical quality characteristics of tomato fruit: (A) lycopene (B), vitamin C, (C) nitrate. Values are presented as means ±SE. Distinct letters indicate statistically significant differences according to Fisher's least significant difference (LSD) test ($p < 0.05$)

coenzymes, prosthetic groups, vitamins, and secondary metabolites, N and S have substantial regulatory impacts on the growth, yield, and nutritional quality of crops [Gigolashvili and Kopriva 2014]. In agricultural productivity, N and S not only have individual roles but also interact with each other [Liu et al. 2020]. Khalili et al. [2024] emphasize that the synergistic effects between N and S play a crucial role in plant performance. Insufficient S supply impairs plant's efficient utilization of applied N [Kumar et al. 2017]. In the current study, the application of 11.5 mM N and 0.625 mM S, with an N/S balance of 9.20, resulted in the highest tomato yields and average fruit weight. Fruit yield decreased in applications where the N/S balance in the nutrient solution was above or below 9.20 (Fig. 1A). Furthermore, nutrient solutions with N/S balance above 9.20 and below 4.66 reduced the average fruit weight (Fig. 1B). However, the effect of N/S ratios in the nutrient solution on fruit number was insignificant (Fig. 1C). Janzen and Bettany [1984] found that optimum canola yields are achieved by maintaining a balanced availability of N and S. The authors confirmed that the optimal ratio was estimated to be 7:1 and reported that excessive S application in relation to N availability resulted in overwhelming S accumulation in the plant tissues and diminished seed production. Głowacka et al. [2023] highlight that an adequate supply of these nutrients is essential for plants to fully exploit their yield potential.

The shape of fleshy fruits considerably affects their utilization and consumer preference in distinct geographical locations [Li et al. 2023]. The fruit shape is usually defined by the fruit diameter, the fruit length and the fruit shape index, which indicates the ratio of fruit diameter to fruit length [Li et al. 2023]. It was observed that fruit size and diameter were larger in tomatoes fed with nutrient solutions with the N/S balance of 50.00 and 9.20. Nevertheless, the size and diameter of the fruit exhibited a decline when the N/S ratios reached 4.66 and 2.92 in the nutrient solution (Table 2). This was due to a decrease in the N concentration or an increase in the S concentration in the nutrient solution. The biophysical quality characteristics (fruit length, fruit diameter and core diameter) of pineapple fruits increased with increasing N dosage, as reported by Omotoso and Akinrinde [2013]. Grasso et al. [2022] noted that when the N supply to the melon plant was reduced too much, the formation of small fruits and fruit deformations was observed, resulting in a 58% increase in the proportion of fruit waste. In the current study, the fruit shape index showed no response to variations in N or S content, and no statistically significant differences were found between all treatments (Table 2). The current findings regarding this parameter were in agreement with those reported by Cai et al. [2023]. Fruit firmness is an important characteristic that ensures the storage and transport of tomatoes, as firmer fruit can better resist damage [Li et al. 2020]. Conversely, excessive softening during the ripening of fleshy fruit causes physical damage and increases susceptibility to infection, ultimately reducing quality and leading to significant losses in the supply chain [Shi et al. 2023]. In this study, there was no effect of increasing the level of N fertilization from 9.5 to 12 mM on the firmness of the fruit (Table 2), which is in agreement with Kaniszewski et al. [2019]. In contrast, Frías-Moreno et al. [2020] reported that the tomato fruit firmness increased with escalating doses (30 mM) of N till one point, but then firmness declined. Though a sufficient amount of N is required to have adequate firmness in tomatoes, higher amounts of N can lead to a weaker translocation of Ca into the fruit [Frías-Moreno et al. 2020]. A reduction in Ca accumulation in the fruit leads to loss of cell wall integrity and firmness [Zhang et al. 2020].

The pH value is an important quality characteristic in the processing of tomatoes. In the present study, depending on the treatment, the pH values in the tomato juices were between 4.52 and 4.63 (Fig. 2A). Tomatoes usually have adequate acidity to sustain a pH value below 4.6 and are, therefore, not categorized as low-acid foods. For this reason, tomatoes do not require the more drastic thermal treatments needed to kill spoilage microorganisms in foods classified as low in acids to ensure food safety [Siueia et al. 2020]. Desirable values of total soluble solids in tomato fruits are between 4 and 9% [Duma et al. 2015] for fresh consumption or for the processing industry. In the preset study, total soluble solid values were within this range (Fig. 2B). The soluble solids give the fruit a particular flavor depending on the sugar content. Nevertheless, the changes in this content probably depend on the genotype and various factors that influence the fruit's capability to import assimilated photosynthesis. Therefore, using varieties in which this trait can be guaranteed is essential to allow greater consumer acceptance [Siueia et al. 2020]. The acidity of the fruit is a significant factor in determining the taste of the tomato products [Zhang et al. 2023a]. Citric acid is the primary carboxylic acid found in tomatoes and accounts for most of the total titratable acidity [Parra-Torrejón et al. 2023]. In the present study, significant differences in titratable acidity were observed in tomato fruits at different N/S ratios. Titratable acidity in tomato fruit was the lowest in the application ($N_{12.5}$:$S_{0.125}$) with the highest N/S ratio (Fig. 2C). This could be due to the degradation of organic acids by nitrogen, which is transported into the fruit as a result of an increased N concentration in the growth medium. One of the most notable indicators of the quality of tomato fruits and their technological traits is the dry matter content [Kurina et al. 2021]. In the current study, the dry matter content of the cultivated tomato fruits varied between 6.77 and 7.37% (Fig. 2D). The results of the current study on dry matter content are in agreement with the findings of another study [Alenazi et al. 2020], in which the dry matter content of tomato fruits was between 5.95 and 7.85%. Fruits with a high concentration of dry components taste good, produce a greater yield during processing, and have superior transportability and quality retention during storage [Kurina et al. 2021].

Crop productivity and sensory quality are among the aspects that receive the most attention. However, consumers have become more interested in the nutritional value of fruits and vegetables because they want to buy food that is good for their health [Scarano et al. 2020]. In this regard, tomato fruit is an important source of carotenoids such as lycopene, which has been linked to a lower risk of cancer and cardiovascular disease [Shah et al. 2021]. Lycopene is the main carotenoid that gives fruits their red pigmentation [Gupta et al. 2024]. The study showed that the treatment with the highest N concentration (12.5 mM) had the highest lycopene content (7.69 mg 100 g^{-1} FW) (Fig. 3A). In contrast, San-Martín-Hernández et al. [2022] observed a decrease in the lycopene content of the tomato when the N concentration in the nutrient solution increased from 10 to 16 mM. Lycopene concentration in tomato fruit can be affected by environmental factors, agronomic practices, and postharvest conditions [Lima et al. 2022]. Vitamin C is of great importance in human nutrition, not only for its role as an antioxidant but also for its positive effect on the availability of dietary iron [See et al. 2024]. In this study, vitamin C in tomato fruit was the lowest in the application ($N_{12.5}$:$S_{0.125}$) with the highest N/S ratio (Fig. 3B). These results are in line with Bénard et al. [2009] who found a decrease in the vitamin C content owing to an increase in the supply of N. The activities of crucial enzymes and metabolites involved in the degradation and recycling processes of vitamin C increased with an increasing N supply [Zhang et al. 2023b]. Nitrate is a chemical compound naturally present in fruits and vegetables [Uddin et al. 2021]. Nitrate acts as a signaling molecule that triggers the production of NO_3^--related genes responsible for the processes of absorption, transport, assimilation as well as vegetative and reproductive development [Aluko et al. 2023]. Plants take up NO_3^- from the root, assimilate NO_3^- and then translocate it to the shoot, where it can be re-mobilized in sink organs [Iqbal et al. 2020]. Excessive nitrate accumulation in vegetables is a prevalent concern that may present a risk to human health [Bian et al. 2020]. In this study, NO_3^- concentrations in tomatoes were considerably lower than World Health Organization (WHO) standards (Fig. 3C). Nitrate concentration in crops depends on the type and variety of the crop, environmental factors, and agricultural practices [Ferysiuk and Wójciak 2020].

CONCLUSIONS

The optimum N/S balance in the nutrient solution varied depending on the characteristics analyzed. The N/S balance of 9.20 in the nutrient solution resulted in high total fruit yield, average fruit weight, fruit size, and width. It was found that the N/S balance in the nutrient solution above or below 9.20 had negative effects on yield and yield parameters as well as on some biophysical quality characteristics of the fruit. However, the N/S balance in the nutrient solution had no influence on the number of fruits, the firmness and shape index and the pH value of the fruits. Based on these results, ensuring balanced plant nutrition is crucial to achieving a high-yielding, high-quality crop that meets the expectations of the end consumer.

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