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TOMATO FRUIT QUALITY BETWEEN CLUSTERS IS DIFFERENTIALLY AFFECTED BY NITROGEN AND POTASSIUM SUPPLY

LA CALIDAD DEL FRUTO DE TOMATE ENTRE RACIMOS ES AFECTADA DIFERENCIALMENTE POR EL SUMINISTRO DE NITRÓGENO Y POTASIO

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SUMMARY

Fruit quality is significantly affected by the nutrient status of plants; nonetheless, it has not yet been deeply explored how nitrogen (N) and potassium (K) supply affects tomato fruit quality between clusters during the vegetative and reproductive stages of the crop. The aim of this study was to evaluate the effects of N and K on fruit quality parameters of three clusters of hydroponically grown tomato (*Solanum lycopersicum* L.). Nitrogen (10, 12, 14 and 16 mol_c N m^{-3}) was evaluated at the vegetative stage, and potassium (5, 7, 9, 11 and 13 mol_c K m^{-3}) at the reproductive stage. The evaluated N and K concentrations showed significant main effects on the quality attributes total soluble solids, citric acid percentage, reducing sugars, color and lycopene concentration; yield was affected only by K, while the effects of N × K interaction were not significant. Increasing N concentrations from 10 to 16 mol_c m^{-3} enhanced hue angle, brightness, reducing sugars and citric acid percentage, but decreased total soluble solids and lycopene. As K increased from 5 to 13 mol_c m^{-3} in the nutrient solution, total soluble solids, citric acid, reducing sugars, lycopene, yield and fruit brightness increased, but hue decreased. Total soluble solids, reducing sugars and lycopene gradually increased from the first to the fifth cluster, while yield, color attributes of hue and brightness tended to decrease as the crop cycle progressed. Titratable acidity percentage showed no clear trends between clusters. It is concluded that N and K differentially affect tomato quality between clusters.

Index words: *Solanum lycopersicum* L., hydroponics, K nutrition, N nutrition, reducing sugars, tomato clusters.

RESUMEN

La calidad del fruto es afectada significativamente por el estado nutricional de las plantas; no obstante, aún no se ha explorado a profundidad la manera en que el suministro de nitrógeno (N) y potasio (K) afecta la calidad del fruto de tomate entre racimos durante las etapas vegetativa y reproductiva del cultivo. El objetivo del presente estudio fue evaluar los efectos del N y K en los parámetros de calidad del fruto de tres racimos de tomate (*Solanum lycopersicum* L.) cultivado en hidroponía. Se evaluó nitrógeno (10, 12, 14 y 16 mol_c N m^{-3}) en la etapa vegetativa y potasio (5, 7, 9, 11 y 13 mol_c K m^{-3}) en la etapa reproductiva. Las concentraciones de N y K evaluadas mostraron efectos principales significativos en los atributos de calidad sólidos solubles totales, porcentaje de ácido cítrico, azúcares reductores, color y concentración de licopeno; el rendimiento fue afectado sólo por K, mientras que los efectos de la interacción N × K no fueron significativos. El incremento de la concentración de N de 10 a 16 mol_c m^{-3} mejoró el ángulo de tonalidad, el brillo, y los porcentajes de azúcares reductores y de ácido cítrico, pero disminuyeron los sólidos solubles totales y el licopeno. A medida que K aumentó de 5 a 13 mol_c m^{-3} en la solución nutritiva, los sólidos solubles totales, ácido cítrico, los azúcares reductores, el licopeno, el rendimiento y el brillo del fruto se incrementaron, pero la tonalidad disminuyó. Los sólidos solubles totales, los azúcares reductores y el licopeno aumentaron gradualmente del primer al quinto racimo, mientras que el rendimiento, los atributos de color de matiz y el brillo tendieron a la baja a medida que avanzó el ciclo de cultivo. El porcentaje de acidez titulable no mostró tendencias claras entre racimos. Se concluye que el N y el K afectan diferencialmente la calidad del tomate entre racimos.

Palabras clave: *Solanum lycopersicum* L., azúcares reductores, hidroponía, nutrición nitrogenada, nutrición potásica, racimos de tomate

INTRODUCTION

Tomato (*Solanum lycopersicum*) is one of the most important crops in the world economy, with an annual production of more than 180 million tons (FAO, 2019). Tomato fruit is mainly composed of water, soluble solids (especially sugars) (Beckles, 2012), organic acids (citric and malic), biomolecules such as carotenoids (which impart the characteristic color) and vitamins A and C (Agius *et al*., 2018; Dumas *et al*., 2003).

Quality and biochemical composition of fruits mainly depend on the cultivar, agronomic practices, and the stage of maturity of the fruit (Duma *et al*., 2015). Among agronomic practices, plant nutrition plays a pivotal role in tomato yield and quality (Wang and Xing, 2017). It is important to note that the nutrient requirements of plants vary between developmental stages. In hydroponically grown tomato, application of N and K in the nutrient solution at periods of increased demand during fruit growth promotes optimal nutrition, maximum growth and increased marketable fruit

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quality (Fandi *et al*., 2010); however, excessive N fertilization decreases important quality traits such as pH, total soluble solids, soluble sugars, and the content of glucose and fructose, as well as color parameters (Parisi *et al*., 2006).

Crops grown in protected environments such as greenhouses open the possibility of controlling the supply of water and nutrients (Signore *et al*., 2016); however, to provide optimal conditions, it is important to use balanced nutrient solutions and different ionic proportions that meet the nutritional requirements of crops (Ramírez *et al*., 2012); furthermore, in tomato, fruit quality is significantly affected by the position of the fruit in the cluster (Coyago-Cruz *et al*., 2017); nonetheless, the effects of the contribution of N and K according to the phenological stage of the crop on fruit quality considering its cluster of origin have not yet been fully investigated. Hypothesizing that the supply of primary macronutrients may differently affect fruit quality between clusters, the aim of this study was to evaluate the effect of nitrogen nutrition at the vegetative stage and potassium nutrition at the reproductive stage on fruit quality attributes from different clusters of hydroponically grown round-type tomato Charleston.

MATERIALS AND METHODS

Plant material, treatments and experimental design

The experiment was carried out using 37-day-old seedlings of round-type tomato cv. Charleston, which were grown under hydroponic greenhouse conditions. The crop was established from July to December, with an average photosynthetically active radiation (PAR) of 260 W m^{-2}; a data logger (Hobo®, Cape Cod, Massachusetts, USA) recorded temperatures of 33 to 25 °C maximum and 16 to 8 °C minimum and relative humidity of 98 to 95 % maximum and 42 to 32 % minimum.

The study factors were N and K, with 4 and 5 levels respectively, generating 20 treatments. Treatments were assigned to experimental units under a completely randomized experimental design with six replications using a split plot arrangement. The N factor was established in the whole-plot and K in the split-plot. The experimental unit was a plant established in a 13 L pot, which was filled with inert volcanic gravel, commonly known as 'tezontle' (particle diameter ≤ 12 mm).

The levels of the nutrient solution with N (10, 12, 14 and 16 $mol_c\ m^{-3}$) were applied during the first 45 days after transplantation (dat) at the vegetative stage; then the levels of K (5, 7, 9, 11 and 13 $mol_c\ m^{-3}$) were applied from 46 to 170 dat at the reproductive stage of the tomato crop under hydroponic conditions. For the formulation of the tested nutrient solutions, Steiner's universal nutrient solution (Steiner, 1984) was used as a reference, in which the corresponding NO_3^- and K^+ concentrations were adjusted, maintaining an osmotic potential of -0.072 MPa and a pH of 6.0 in all concentrations (Table 1). The water used in the experiment was obtained from a deep well located in the area of influence of Colegio de Postgraduados, Campus Montecillo in Mexico (19° 27' 49.72'' N, 98° 54' 19.66'' W, 2250 masl) and had the following average composition (in mg L^{-1}): S 19.90, K 3.61, Ca 26.61, Mg 30.18, B 0.08, Na

Table 1. Composition of evaluated nutrient solutions according to the NO_3^- and K^+ concentration.

Concentration ($mol_c\ m^{-3}$)	Concentration of ions ($mol_c\ m^{-3}$)						
	NO_3^-	$H_2PO_4^-$	SO_4^{2-}	K^+	Ca^{2+}	Mg^{2+}	NH_4^+
NO_3^-							
10	7.80	1.63	11.38	6.37	8.19	3.64	2.60
12	9.10	1.39	9.73	6.02	7.74	3.44	3.03
14	10.33	1.17	8.18	5.68	7.31	3.25	3.44
16	11.50	0.96	6.71	5.37	6.90	3.07	3.83
K^+							
5	12.41	1.03	7.24	5.17	10.74	4.77	----
7	12.00	1.00	7.00	7.00	9.00	4.00	----
9	11.61	0.97	6.77	8.71	7.37	3.27	----
11	11.25	0.94	6.56	10.31	5.84	2.60	----
13	10.91	0.91	6.36	11.82	4.41	1.95	----

39.48, Fe 0.01, and Zn 0.01, with EC = 0.76 dS m^{-1} and pH of 7.1.

Seedlings were irrigated using Steiner nutrient solution (Steiner, 1984) with N and K concentrations as indicated above, according to the phenological stage. Eight irrigations were applied with a drip irrigation system, a total volume of 1072 mL per day were provided during the first 30 dat; subsequently, 16 irrigation applications of 140 mL each were provided daily until the end of the study (170 dat).

Variables evaluated

The following measurements were made on completely red ripe fruits from three clusters (first, third and fifth) at 110, 131 and 167 dat:

Total soluble solids (TSS)

This variable was determined from three drops of juice obtained from fruits cut longitudinally, the juice was placed in the cell of a digital refractometer (ATAGO PR-100, Honcho, Itabashi-Ku; Tokyo, Japan) with a scale ranging from 0 to 32 %, expressing the TSS value in percentage at 20 °C.

Titratable acidity (TA)

This determination was peformed as described by Boland (1990), using the citric acid value as a correction factor, since it is the organic acid found in highest proportion in tomato fruits (Agius *et al*., 2018), and therefore, this variable is reported as a percentage of citric acid equivalents. The juice of fruits was extracted with a Turmix juicer (Ocoyoacac, Mexico); then, 5 mL of the juice were taken and three drops of phenolphthalein were added, it was titrated with a sodium hydroxide solution of known normality (NaOH 0.1 N), until reaching a pH value of 8.2; then, the acidity of the juice was calculated with the following equation:

$$\text{Citric acid (\%)} = \frac{V_{NaOH}\,(mL) \times N_{NaOH}\,(meq\ mL^{-1}) \times \text{milliequivalents of citric acid}\ (0.0064\ g\ meq^{-1})}{\text{V juice (mL)}} \times 100$$

Reducing sugars

The concentration of reducing sugars was determined according to the methods of Nelson (1944) and Somogyi (1952). Based on the extraction of sugars from 1 g of tomato juice obtained with the Turmix juicer and the development of color with Nelson's reagent and ammonium arseno-molybdate, samples were read at 540 nm in a spectrophotometer (Spectronic 20, Bausch and Lomb; Bridgewater, New Jersey, USA). The amount of sugars expressed in g kg^{-1} fresh fruit (FF) was calculated taking as reference the calibration curve with D-glucose solutions (Sigma-Aldrich; St. Louis, Missouri, USA) of known concentration.

Color

Values of L, *a* and *b* of the CIE L**a***b** color system were obtained with a colorimeter (Hunter Lab D25-PC2; Reston, Virginia, USA) at two opposite points on the equatorial zone of the fruit; subsequently, these values were used to calculate the hue angle with the formula: hue (°) = $\tan^{-1}$ (*b*/*a*), while brightness was obtained directly with the colorimeter (McGuire, 1992).

Lycopene

Using the equation proposed by Arias *et al*. (2000), the concentration of lycopene (in mg kg^{-1} FF) was calculated indirectly using the *a* and *b* values, which are chromaticity coordinates for *a** = red/green coordinate and *b** = yellow/blue coordinate, obtained in the fruit color measurement described above.

$$Lycopene\ (mg\ 100\ g^{-1}\ FF) = 11.848 \times \frac{a}{b} + 1.541$$

Firmness

Before making the chemical determinations and after measuring the color, the firmness was measured at two opposite points in the equatorial zone of the fruit using a texture analyzer (FDV-30, Greenwich, Connecticut, USA) adapted with an 8 mm diameter conical strut. Two punctures were made in the fruit, and the corresponding values were reported in Newtons of force (N) (San Martín-Hernández *et al*., 2012).

Yield

The yield, reported in g per plant, was evaluated in the second, fourth and sixth clusters. Tomato plants were grown to four fruits per cluster, with the remaining fruits pruned when the fourth established fruit was between 1 and 2 cm in size.

Statistical analysis

To investigate the relationship between the study factors (N and K) and the response variables, the following model was used, adapted to a completely randomized design with a split-plot arrangement.

$$Y_{ijk} = \mu + N_i + \varepsilon_a + K_j + N * K_{ij} + \varepsilon_{ijk}$$

Where: Y_{ijk} = response variable for the *ijk* experimental unit, μ = overall mean, N_i = effect of the ith level of N, $\mathcal{E}_a$ = experimental error of large plot, K_j = effect of the jth level of K, $N \times K_{ij}$ = effect of the N × K interaction, $\mathcal{E}_{ijk}$ = random experimental error. $\mathcal{E}_a \sim$ NI(0, σ_a^2) and $\mathcal{E}_{ijk} \sim$ NI(0, σ^2) are assumed to be normal, independent, with zero mean and common variance σ^2.

An analysis of variance (ANOVA) was performed and means were compared with the Tukey HSD test ($P \leq 0.05$). The verification of the assumptions of the model was performed using the Bartlett's test, the Shapiro-Wilk normality test and the Durbin-Watson statistic, which were reasonably normal, with homogeneity of variances and independence. All statistical calculations were carried out using the SAS Ver. 9 software.

RESULTS AND DISCUSSION

The N and K concentrations evaluated in the nutrient solution of the hydroponically-grown tomato showed major and significant effects ($P \leq 0.05$) on the quality attributes TSS, % TA, reducing sugars, color (hue and brightness), lycopene, firmness and yield of fruits harvested when completely red (*i.e.* at commercial maturity stage); nonetheless, the effects of N × K interaction on these variables were not significant (Table 2). Furthermore, the fruit quality indices showed differential responses among clusters.

Total soluble solids (TSS)

Nitrogen concentrations in the nutrient solution affected the TSS percentage only in fruits of the first cluster, while the effects of K were observed in the three evaluated clusters (Table 2). A negative relationship between the content of TSS and the concentration of N in fruits of the first cluster, since increasing the N concentration in the nutrient solution from 10 to 16 mol$_c$ m^{-3}, causes a reduction of 9.6 % in this variable (Table 3). Reductions of TSS in tomato due to increased N supply have been previously reported (Parisi *et al*., 2006); furthermore, by maintaining the same N supply but increasing the water supply from 70 to 90 % of field capacity, reductions of TSS were also observed (Hui *et al*., 2017). This response can be attributed to a "dilution effect" of TSS, since a higher supply of N and water causes greater growth of the fruit, with the consequent dilution of solids. Desirable values of TSS in tomato fruits are between 4 and 9 % (Duma *et al*., 2015) for fresh consumption or for the processing industry. In this study, TSS values were within this range.

In general, there is a positive effect of K on TSS (Table 3). Within the TSS content, sugars are the main constituents (65 %) (Beckles, 2012), which have been associated with K in transit from source (*i.e.* leaves) to sink (*i.e.* fruits) organs (Engels *et al*., 2012). The highest TSS contents were recorded in the fruits of the first and fifth clusters with K concentrations in the nutrient solution equal to or greater than 11 mol$_c$ m^{-3}, while similar responses were obtained in fruits of the third cluster, with K values equal to or greater than 7 mol$_c$ m^{-3} (Table 3); however, the TSS tended to increase as the clusters developed (Table 3).

Titratable acidity (TA)

The effects of N on fruit acidity were evident only in the fifth cluster, while K exerted significant effects on the three clusters analyzed (Table 3). The highest acidity was obtained by fruits from the first cluster regardless of the N concentration in the nutrient solution, while the lowest acidity was found in fruits of the third cluster. Incresing N concentrations from 10 to 12 mol$_c$ m^{-3} resulted in a 7 % increase in fruit acidity in the fifth cluster, and this increase was maintained at 14 and 16 mol$_c$ m^{-3} N (Table 3). Similarly, it has also been reported that increasing N fertilization increases the concentration of organic acids in tomato cv. Jinpeng 10 (Wang and Xing, 2017).

The increase in K in the nutrient solution also gradually increased the acidity of the fruit; consequently, the lowest TA was observed in plants treated with 5 mol$_c$ K m^{-3}. The largest increases in this attribute with 29 % in the first cluster, followed by 21 % in the third and 18 % in the fifth cluster were related to the increase in K concentration from 5 to 13 mol$_c$ K m^{-3} (Table 3); likewise, Caretto *et al*. (2008) also reported increased TA contents by increasing K in the nutrient solution; however, in this study the values were 14 % higher using similar concentrations of K (*i.e.* 150 to 450 mg K L^{-1} corresponding to 3.8 to 11.5 mol$_c$ m^{-3}). This confirms a positive relationship between the concentration of K in the nutrient solution and the TA of the fruit (Rebouças Neto *et al*., 2016), which also coincides with an increase in the concentration of citric acid (Çolpan *et al*., 2013). It is important to highlight that the content of ascorbic acid and citric acid, pH and total soluble solids in the fruits confer significant differences to the tomato flavor (Berrospe-Ochoa *et al*., 2018).

Reducing sugars

Reducing sugars showed a gradual increase from the first to fifth cluster, although significant effects of N were only observed in fruits from the first and third cluster. Interestingly, the effects of K were observed in the three clusters evaluated (Table 1). Potassium plays a fundamental role in photosynthesis and transpiration and is highly demanded by plants, which significantly affects

Table 2. ***P*-values and coefficients of variation (CV) of concentrations of N applied at the vegetative stage and of K at the reproductive stage and their interaction on postharvest quality indices in fruits of three clusters of tomato grown hydroponically.**

Quality index	Cluster	Source of variation			CV (%)
		N	K	N × K	
Total soluble solids	1st	0.0043 *	<.0001 *	0.9798 ns	8.4
	3rd	0.1934 ns	<.0500 *	0.9992 ns	10.0
	5th	0.1127 ns	0.0008 *	0.9986 ns	7.9
Titratable acidity	1st	0.4071 ns	<.0001 *	0.7686 ns	11.2
	3rd	0.1917 ns	<.0001 *	0.3583 ns	11.4
	5th	0.0083 *	<.0001 *	0.7905 ns	12.2
Reducing sugars	1st	0.0103 *	0.0051 *	0.9687 ns	14.0
	3rd	0.0034 *	<.0001 *	0.6190 ns	14.5
	5th	0.3803 ns	<.0001 *	0.9990 ns	12.9
Hue	1st	0.0123 *	0.0001 *	0.5910 ns	5.5
	3rd	0.0125 *	<.0001 *	0.9267 ns	6.9
	5th	0.7303 ns	<.0001 *	0.9974 ns	6.5
Brightness	1st	0.0016 *	0.0181 *	0.9084 ns	4.6
	3rd	0.0856 ns	0.0023 *	0.9693 ns	6.0
	5th	0.3303 ns	0.8399 ns	0.8616 ns	5.0
Lycopene	1st	0.0138 *	<.0001 *	0.6458 ns	7.5
	3rd	0.0130 *	0.0002 *	0.9050 ns	8.5
	5th	0.7531 ns	<.0001 *	0.9989 ns	7.8
Firmness	1st	0.6345 ns	0.8798 ns	0.5265 ns	18.1
	3rd	0.6562 ns	0.7825 ns	0.9775 ns	22.2
	5th	0.0199 *	0.9924 ns	0.8320 ns	19.0
Yield	2nd	0.4515 ns	0.0002 *	0.8908 ns	10.9
	4th	0.6588 ns	0.0300 *	0.9990 ns	11.2
	6th	0.1020 ns	0.0156 *	0.6229 ns	13.4

*: statistically significant ($P \leq 0.05$), ns: non-significant, CV: coefficient of variation.

crop production and productivity (Wang *et al*., 2015). The increase in N also enhanced reducing sugars (fruits of the first and third cluster), but statistical differences were observed only in plants treated with 10 mol_c N m^{-3} when compared to the other treatments (Table 3).

Sugars of the fruit, mainly represented by glucose and fructose (reducing sugars) (Agius *et al*., 2018), are reported to increase when tomato is fertilized with N at an adequate level (Hui *et al*., 2017). Similarly, when the K concentration increased from 5 to 13 mol_c m^{-3}, the reducing sugars increased by 16, 19 and 20 % in fruits of the first, third and fifth cluster, respectively. The maximum concentrations of reducing sugars, 32.0, 42.3 and 54.0 g kg^{-1} FF from the first to the fifth cluster, were obtained with the highest K concentration (Table 3). There are direct relationships between the content of reducing sugars and the increasing of K in tomato (Almeselmani *et al*., 2009). In addition to its role in photosynthesis, the increased supply of K promotes the translocation of photoassimilates, mainly as sucrose, to sink organs (Engels *et al*., 2012) such as the fruit. In the early stages of fruit development, starch accumulates at the expense of sucrose. In the phloem, K is usually transported from older tissues to growing organs such

Table 3. Total soluble solids (TSS), titratable acidity (TA) and reducing sugars in tomato fruits from the first (1st C), third (3rd C) and fifth (5th C) clusters, according to the supplied concentrations of N at the vegetative stage and K at the reproductive stage of the crop. Data for the N × K interaction are not shown as they were not significant.

Source of variation	TSS (%)			TA (% citric acid)			Reducing sugars (g kg^{-1} FF)		
	1st C	3rd C	5th C	1st C	3rd C	5th C	1st C	3rd C	5th C
N (mol_c m^{-3})									
10	5.23 a	6.12 a	7.29 a	0.77 a	0.53 a	0.57 b	27.74 b	36.41 c	49.02 a
12	4.89 ab	5.99 a	6.94 a	0.73 a	0.56 a	0.61 a	29.21 ab	39.95 ab	50.88 a
14	4.82 b	6.11 a	7.10 a	0.78 a	0.52 a	0.61 a	30.89 a	37.63 bc	49.95 a
16	4.73 b	5.82 a	7.23 a	0.76 a	0.54 a	0.60 a	30.97 a	41.03 a	48.57 a
HSD	0.35	0.42	0.40	0.09	0.06	0.04	2.76	3.32	3.91
K (mol_c m^{-3})									
5	4.70 b	5.73 b	6.86 b	0.65 c	0.486 c	0.55 c	27.56 b	35.49 b	44.96 c
7	4.77 b	5.92 ab	7.02 b	0.75 b	0.51 bc	0.56 bc	28.7 ab	35.38 b	46.90 bc
9	4.85 b	6.08 ab	7.06 b	0.77 b	0.54 b	0.60 abc	29.82 ab	38.80 ab	50.57 ab
11	5.00 ab	6.10 ab	7.20 ab	0.80 ab	0.56 ab	0.62 ab	30.41 ab	41.77 a	51.60 ab
13	5.27 a	6.24 a	7.56 a	0.84 a	0.59 a	0.65 a	32.02 a	42.32 a	53.99 a
HSD	0.33	0.48	0.46	0.07	0.05	0.06	3.34	4.53	5.17

Means with different letter in columns are statistically different (Tukey, P ≤ 0.05), FF: fresh fruit, HSD: honestly significant difference.

as new leaves and developing fruits (Mengel and Kirkby, 2001). In source tissues, K can stimulate sucrose loading, while its deficiency can lead to sugar accumulation due to reduced starch synthase activity, reduced phloem loading and impaired sucrose export (Zörb *et al*., 2014). Since K regulates starch metabolism during fruit ripening, accumulation rates of reducing sugars such as fructose and glucose can be observed in tomato fruits (Beckles, 2012). These facts are consistent with the results obtained in this study, since a positive response was observed in reducing sugars concentration, which was proportional to the magnitude of the K provided in the nutrient solution.

Color

Hue

Both N and K affected fruit color (Table 2). In tomato, an increase in N fertilization from 0 to 250 kg ha^{-1} resulted in delayed fruit maturity and adverse effects on fruit color development (Parisi *et al*., 2006). These responses fully agree with those detected in this study, since hue in fruits of the first (42.8°) and third (35.8°) clusters was the lowest at the lowest level of N, and increased by 5.6 and 5.9 % when changing the level of N from 10 to 14 and from 10 to 16 mol_c m^{-3} respectively. These increases in hue caused by the increase in N are due to the reduced red color in the fruits according to the L*c*h* color space (McGuire, 1992); on the contrary, the increase in K concentration from 5 to 13 mol_c m^{-3} induced a reduction of 7, 10 and 11 % in the hue angle compared to the hue in fruits of the first (45.3°), third (38.8°) and fifth (37.0°) clusters, observed with the lowest level of K tested (Table 4). The increasing of K fertilization in field-grown tomatoes improved the value of the hue angle (Hartz *et al.*, 2005), which is in full agreement with the results obtained in this research, since the K treatments increased the reddish hue of fruits.

Brightness

The effects of N on brightness were observed only in fruits of the first cluster, and those of K in the first and third clusters (Table 2). The highest mean for brightness was observed with the highest concentration of N. Similar results were observed in apple fruits when increasing doses of N (from 9 to 105 g per plant) were applied (Wang and Cheng, 2011). Regardless of the K added to the nutrient solution, fruit brightness gradually decreaed in fruits from the first to the fifth cluster; however, when K increased from 5 to 13 $mol_c\ m^{-3}$, the brightness proportionally increased by 5 % from the minimum values recorded in the first and third clusters, with K concentrations ≥ 11 $mol_c\ m^{-3}$ being the most appropriate to increase fruit brightness (Table 4); conversely, when increasing K fertilization from 0 to 800 kg ha^{-1} in field-grown tomatoes, a 7 % reduction in brightness was observed, while the highest value (44) was observed with the lowest K dose applied (Hartz *et al*., 2005).

Lycopene

The study factors influenced lycopene concentration in the fruit: N altered the synthesis of this pigment in the first and third clusters, while K, influenced the three clusters (Table 2). As N increased from 10 to 14 $mol_c\ m^{-3}$ in the nutrient solution, lycopene concentrations decreased by 8 and 6 % compared to the maximum values detected in the first and third clusters respectively, both with N at 10 $mol_c\ m^{-3}$ (Table 4).

Results showed that a low N concentration can improve lycopene concentration in tomato. Lycopene decreased from 68 to 38 mg kg^{-1} in fresh fruits due to increases in N of 1, 12.9 and up to 15.8 $mol_c\ m^{-3}$ (Dumas *et al*., 2003). On the other hand, when tomato is nourished with increasing K, lycopene concentrations significantly increase. In this experiment, when K concentration increased from 5 to 13 $mol_c\ m^{-3}$, the lycopene concentration increased considerably by 10, 12 and 13 % in the first, third and fifth clusters, respectively (Table 4). The lowest lycopene concentration was observed in plants treated with the lowest K, while the highest concentration was observed with K at 13 $mol_c\ m^{-3}$, in the three clusters evaluated (Table 4). Lycopene content of tomato can increase by 35 % when the concentration of K increases from 8 to 9 $mol_c\ m^{-3}$ (Ramírez *et al*., 2012). Potassium is involved in the activation of several enzymes, being phytoene synthase and phytoene desaturase those associated with phytoene and phytofluene, both intermediates in the biosynthesis of lycopene (Taber *et al*., 2008).

Firmness

In fruits of the fifth cluster, firmness was significantly affected by nitrogen supply (Table 1). By increasing the nitrogen supply from 10 to 16 $mol_c\ m^{-3}$, the firmness in fruits of the fifth cluster decreased by 16 % (Table 5). Small increases in the concentration of N during tomato cultivation increase fruit firmness, but when the N supply exceeds 30 $mol_c\ m^{-3}$, this attribute decreases (Frías-Moreno *et al*., 2020) as observed in this investigation. The nitrogen to calcium ratio (N/Ca) is a crucial factor determining fruit firmness in different plant species (Khalil

Table 4. Hue, brightness and lycopene in tomato fruits from the first (1st C), third (3rd C) and fifth (5th C) clusters, according to the applied concentrations of N at the vegetative stage and K at the reproductive stage of the crop. Data for the N × K interaction are not shown due to lack of significance.

Source of variation	Hue (°)			Brightness			Lycopene (mg kg^{-1} FF)		
	1st C	3rd C	5th C	1st C	3rd C	5th C	1st C	3rd C	5th C
N ($mol_c\ m^{-3}$)									
10	42.8b	35.8b	35.6a	31.7b	31.1a	31.4a	144.1a	181.4a	182.0a
12	43.6ab	36.0ab	35.9a	32.8ab	31.0a	31.8a	140.8ab	179.7ab	181.0a
14	45.2a	37.4ab	35.3a	33.5a	31.8a	30.9a	133.9b	171.4ab	184.2a
16	43.9ab	37.9a	35.1a	33.7 a	32.3a	31.1a	139.4ab	169.4b	185.5a
HSD	1.83	1.90	2.05	1.35	1.53	1.42	7.91	10.97	12.86
K ($mol_c\ m^{-3}$)									
5	45.3a	38.8a	37.0a	32.1b	30.9b	31.5a	133.2c	164.1b	174.3c
7	44.7ab	37.3ab	36.9a	32.8ab	30.8b	31.2a	136.0bc	172.3ab	174.8c
9	44.2ab	36.3b	35.7ab	33.0ab	31.3ab	31.5a	137.9bc	178.0a	181.2bc
11	42.9bc	36.2b	34.6bc	33.0ab	32.4a	31.3a	143.6ab	178.8a	188.8ab
13	42.2c	35.3b	33.4c	33.7a	32.4a	31.0a	147.0a	184.0a	197.0a
HSD	1.94	2.03	1.85	1.22	1.52	1.27	8.48	12.03	11.51

Means with different letter in columns within each fertilizer type are statistically different (Tukey, P ≤ 0.05), FF: fresh fruit, HSD: honestly significant difference.

Table 5. Fruit firmness and yield of three tomato clusters, according to the supplied concentrations of N at the vegetative stage and K at the reproductive stage of the crop. Data for the N × K interaction are not shown due to the lack of significance.

Source of variation	Fruit firmness (N)			Yield (g per cluster)		
	1st Cluster	3rd Cluster	5th Cluster	2nd Cluster	4th Cluster	6th Cluster
N (mol_c m^{-3})						
10	3.24a	2.26a	2.09a	1078.44a	970.36a	786.16a
12	3.30a	2.37a	1.97ab	1086.41a	984.20a	764.70a
14	3.36a	2.41a	1.97ab	1112.48a	957.56a	716.01a
16	3.51a	2.39a	1.83b	1111.83a	979.84a	718.05a
HSD	0.615	0.346	0.202	52.144	48.957	89.671
K (mol_c m^{-3})						
5	3.32a	2.26a	1.93a	1035.59c	930.02b	694.47b
7	3.32a	2.33a	1.98a	1063.57bc	968.33ab	739.93ab
9	3.41a	2.45a	1.97a	1111.09ab	981.79ab	758.54ab
11	3.44a	2.45a	1.96a	1148.74a	1019.30a	800.63a
13	3.28a	2.30a	1.95a	1134.59ab	990.64ab	733.24ab
HSD	0.492	0.451	0.323	73.596	66.504	81.755

Means with different letter in columns within each fertilizer type are statistically different (Tukey, $P \leq 0.05$); HSD: honestly significant difference.

and Hammoodi, 2021; Torkashvand *et al*., 2017), while decreases in accumulation of Ca in the fruit result in loss of cellular integrity and reduced firmness (Zhang *et al*., 2020).

Yield

The application of N at the vegetative stage and its N × K interaction did not affect fruit yield analyzed in three clusters; instead, the increase in the level of K at the reproductive stage of the crop affected fruit yield in the second, fourth and sixth clusters (Table 1); in fact, positive relationships between K supply and fruit yield have been previously reported (Taber *et al*., 2008).

Increasing the concentration of K in the nutrient solution from 5 to 13 mol_c m^{-3} improved yield, but the maximum increases, with 11, 10 and 15 % were obtained at 11 mol_c m^{-3} in fruits of second, fourth and sixth clusters, respectively (Table 5). In an experiment conducted under field conditions, the 125 % K-based soil test application via polysulphate surpassed all the other treatments in terms of growth and yield parameters (Navitha *et al*., 2019).

Likewise, fruit weight exhibited a similar trend as yield. The highest average weight per fruit, with 287, 255 and 200 g, corresponding to the second, fourth and sixth clusters, were obtained when K was supplied at 11 mol_c m^{-3}. Potassium plays an important role in the mobilization of carbohydrates from source to sink organs (Engels *et al*., 2012). Equivalent increases of up to 33 % in fruit weight have been reported when potassium fertilization changed from 0 to 141.1 kg ha^{-1} in tomato crop (Sultana *et al*., 2015).

Soluble solids, acidity, color, pigment concentrations, sugars and titratable acidity are the result of interactions of a set of pre-harvest factors; these factors include genetics, environmental elements such as solar radiation, temperature (Gautier *et al*., 2005), humidity, crop management and fertilization levels (Wang and Xing, 2017), as observed in this study. Regarding plant nutrition, N plays a key role as a constituent of most of the essential organic molecules, such as nucleic acids, purines, amino acids, some vitamins, proteins and enzymes (Beatty *et al*., 2016), while N deficiency may reduce yield, its excess favors vegetative growth to the point of causing toxic effects (Leghari *et al*., 2016). In tomato, a high supply of N during cultivation worsens the chemical quality attributes of fruits, including pH, soluble solids content, glucose, fructose and the sugars/total solids ratio (Parisi *et al*., 2006).

Potassium is an essential element involved in vital physiological and biochemical processes, including plant signaling, osmoregulation, maintenance of cation-anion balance, cytoplasmic pH regulation, enzyme activation and protein and starch synthesis (Rogiers *et al*., 2017). It is important to know that K is involved in fruit development

(Almeselmani *et al*., 2009) and sucrose accumulation in tomato (Caretto *et al*., 2008). Although K is not a structural component of plant cells, it is absorbed in large amounts by most crop species, influencing product quality parameters and yield parameters. Fruit quality attributes such as TA, TSS, concentration of citric and malic acids, sugars and carotenoids have been found to be positively associated with increasing K doses, while K deficiencies cause fruits with heterogeneous maturity due to low contents of lycopene (Çolpan *et al*., 2013; Ramírez *et al*., 2012; Rebouças Neto *et al*., 2016). The results reported herein are in full agreement with those aforementioned due to the manipulation of N and K during the vegetative and reproductive stages of tomato, respectively. In addition to the effects attributed to the nutrient management implemented, different trends in each cluster were observed in each cluster, since TSS, reducing sugars and lycopene concentration increased from the first to the fifth cluster (Tables 3 and 4), whereas color attributes such as hue and brightness decreased (Table 4). Titratable acidity showed an irregular response, presenting its maximum value in the first cluster (Table 3).

CONCLUSIONS

The results obtained in this study demonstrate that the cluster on which fruits develop as well as the N and K concentrations supplied significantly affect the quality traits of tomato. Total soluble solids, reducing sugars and lycopene gradually increased from the first to fifth cluster, while yield, color attributes such as hue and brightness tended to decrease as the crop cycle progressed; the citric acid percentage of fruit showed no clear trends. Increasing N from 10 to 16 mol_c m^{-3} increased reducing sugars, hue angle, brightness and citric acid percentages, but decreased total soluble solids and lycopene. On the other hand, as K increased from 5 to 13 mol_c m^{-3} in the nutrient solution, yield, total soluble solids, reducing sugars, lycopene, brightness and fruit acidity increased, but the hue value decreased.

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