

Organic and conventional production of tomato fruit and seed

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ABSTRACT

Objective: To evaluate the effect of two organic and one conventional management practices on the production and quality of fruit and seed from two native and one commercial tomato varieties.

Design/Methodology/Approach: The evaluated treatments included three substrate mixtures: vermicompost + tezontle (3 mm) at a 70:30 v/v ratio (S1), vermicompost + tezontle (5 mm) at a 50:50 v/v ratio (S2), and 100% tezontle (5 mm) (S3). Treatments S1 and S2 were completely organic (fertilized with bat guano and hydrolyzed fish), while S3 was fertilized with the Steiner solution. The following tomato varieties were used: Moneymaker (V1), Campeche 40 (V2), and Riñón (V3). The experiment was conducted in a greenhouse for 120 days.

Results: indicated that the highest fruit yield was obtained with the S3 × V1 combination (2.7 kg plant⁻¹). However, the S2 substrate produced fruits of superior quality, with a firmness of 7.74 N, a titratable acidity of 0.83%, and total soluble solids of 6.87 °Brix, similar to S1. Vitamin C content did not significantly differ between substrates. V3 recorded higher values in titratable acidity (0.94%), vitamin C content (4.1 mg/100 g), and total soluble solids (6.91 °Brix) than the other varieties. Regarding seed quality, S2 and S3 yielded superior physical and physiological characteristics, including 92 and 95% germination percentages, respectively. Likewise, they had an emergence speed of 2.9 and 3.3 radicles/d⁻¹ in aged seeds, respectively.

Findings/Conclusions: These findings suggest that the S2 mixture could be recommended for the commercial organic production of tomatoes.

Keywords: substrate, organic agriculture, vermicompost, quality.

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INTRODUCTION

Tomato is a highly important crop both in Mexico and the whole world, due to its significant economic contribution and its value as a source of vitamins, minerals, and antioxidants. Its nutritional value includes essential minerals such as Ca, P, K, and Na, as well as vitamins A, B1, and B2. These components and their bioactive substances contribute positively to human health (Andrade-Sifuentes *et al.*, 2020). Mexico holds the



11th place worldwide in tomato production, accounting for 1.7% of global production, behind countries such as China, India, and the United States of America. However, it contributes 19% of the total export volume, making it the main tomato exporter worldwide (FAOSTAT, 2020). From 2003 to 2017, Mexico produced an average of 2.5 million tons of tomatoes, recording an average annual value of nearly MXN\$15 billion pesos (SIAP, 2020).

In Mexico, the price of organic tomatoes can be up to 5.8 times higher than conventional ones. Combined with increased yields from crops grown in greenhouses (Murillo-Amador, 2010), this situation results in a significant increase in economic benefits for producers. However, conventional and organic farming methods have considerably different impacts on the environment and human health. As a consequence of the use of pesticides, conventional agriculture contributes to greenhouse gas emissions, water pollution and poses a risk to human health. In contrast, organic agriculture makes a significantly lower contribution to the carbon footprint, mitigates soil erosion, and promotes the restoration of natural ecosystems, formerly polluted by toxic pesticide residues (FAO, 2004). In recent years, Mexico—where 2 million ha are used for chemical-free agriculture—has emerged as one of the world leaders in organic food production. According to the Mexican Society of Organic Production (SOMEXPRO: Sociedad Mexicana de Producción Orgánica), approximately 700,000 ha are used for organic production in Mexico, with an additional 100,000 hectares in the process of converting to organic farming. The leading states in organic food production (Chiapas, Oaxaca, Michoacán, Chihuahua, and Guerrero) account for 82.8% of the total land area dedicated to organic agriculture in Mexico (Borbón *et al.*, 2021).

According to the latest report from the Foreign Agricultural Service of the United States Department of Agriculture, organic product trade between Mexico and the United States is increasing and reached record levels in 2023. Organic tomatoes are one of the top five crops exported to the United States and Canada. For Mexico, selling its organic products to these countries is clearly a priority, given their proximity and efficient transportation channels, despite having numerous free trade agreements with other countries (USDA, 2023).

Throughout its life cycle, tomato production depends on the synergistic interaction of essential factors such as genotype, soil, climate, and water. Yield varies depending on the growing site, the variety used, and the management practices adopted. Furthermore, the use of non-adapted varieties, suboptimal soil and water quality, or an inappropriate planting date can limit both the quantity and quality of the harvest (Murillo-Amador *et al.*, 2010).

Few current studies discuss the effect of organic production on tomato fruit and seed quality. Furthermore, scientific information about this production system in Mexico is scarce, despite its economic relevance and the benefits of consuming natural foods. For a production system to be classified and certified as organic, it must originate from seed produced under organic conditions. Accordingly, ensuring the availability of high-quality organic seed provides the justification for this investigation. Consequently, the aim of this study was to compare the yield, fruit quality, and seed quality of three tomato varieties grown in conventional and organic production systems.

MATERIALS AND METHODS

Experimental Site and Plant Material

The crop was grown in a 500 m² and 3.5 m high greenhouse, in a tunnel with side ventilation and a milky-white thermal polyethylene cover that provided 25% shade. The greenhouse is located at the Experimental Agricultural Field of the Universidad Autónoma Chapingo (UACH: Autonomous University Chapingo) in the State of Mexico, at 2,240 m.a.s.l., with the following coordinates: 19° 20' 55.15" N and 98° 50' 69.32" W. Three indeterminate tomato cultivars were used: 1) **MoneyMaker (MM)**, a round-shaped fruit cultivar widely used as a reference in genetic and physiological studies (Ruíz *et al.*, 2021); 2) the native cultivar **C-40**, with kidney-shaped fruit, originally from Campeche and provided by Mr. Iván Ramírez Ramírez (engineer) from the Plant Breeding Program at the Colegio de Postgraduados (Delgado-Vargas *et al.*, 2022); and 3) the native cultivar **Riñón**, with kidney-shaped fruits, traditionally grown using organic practices at the "Las Cañadas" Agroecological Center in Huatusco, Veracruz. Sowing was carried out on February 23, 2023, in 200-cell polystyrene trays using peat moss (sphagnum, Premier Tech Horticulture[®]) as the substrate. Fertigation with 50% Steiner solution began 15 days after sowing.

Substrates

Transplanting took place at 35 days after sowing (das) into 40 × 40 cm black polyethylene bags (pots), each filled with 15 L of substrate and one plant per pot. To select the appropriate substrate mixture for the organic treatments, a minimum total porosity test was performed. Substrate mixtures were chosen based on their suitability within the optimal range for total pore space and for water and air retention for root development. The substrates used in this experiment met the criteria established by Bilderback *et al.* (2005), which include 50% to 85% total pore space, 10% to 30% air capacity, and 25% to 35% water retention. For this purpose, five substrate mixtures with different ratios of vermicompost (Madre Tierra[®] Company) and tezontle were analyzed (results not shown). The 40:60 mixture (tezontle:vermicompost) with 3 mm tezontle particles (Substrate 1, S1), and the 50:50 mixture with 5 mm tezontle particles (Substrate 2, S2), were selected and compared with Substrate 3 (S3 or control), which consisted only of tezontle with particles smaller than 5 mm and was managed using a conventional (non-organic) hydroponic system.

Crop Management

The pots were arranged in double rows at a density of 3.8 plants m⁻². Three days after transplanting (dat), 1 mL L⁻¹ of amino acids was applied. *Fusarium oxysporum* was detected at 12 dat, and as result, 3 mL L⁻¹ of Bayer[®] Cupravit was applied three times, at 15 days intervals starting from the day of detection. Powdery mildew (*Oidiopsis taurica*) was also detected at 75 dat, requiring the application of 7 mL L⁻¹ of *Bacillus subtilis* QST 713 (SERENADE, Bayer[®]) every 15 days until the end of the crop cycle.

The main pest observed was the whitefly (*Bemisia tabaci*). In the organic treatments, 5 g L⁻¹ of Cactucentro[®] diatomaceous earth was applied at 17 dat to control the infestation.

Additionally, a dose of 20 mL L⁻¹ of Cactucentro[®] potassium soap combined with neem was applied once per week until the end of the crop cycle. In the conventional treatment (S3), the commercial insecticide Confidor[®] 350 SC was applied at 17 dat. Subsequently, the same potassium soap and neem mixture used in the organic treatments was also applied. Blue and yellow polypropylene chromatic traps were interspersed throughout the experimental area. The plants were pruned to a single main stem, removing senescent leaves every 7 d and leaving only 5 fruits per bunch. The apex was pinched after the fifth bunch appeared, leaving two leaves at the top to protect the fruits from excessive solar radiation. Nutrition in the organic treatments included three components: vermicompost incorporated into the substrate; diluted bat guano (Vita[®]) applied at 10 mL L⁻¹ per plant weekly from transplant until 60 dat; and the organic fertilizer Vitalex (Química Sagal[®]) and the pH regulator DAP-PLUS (Química Sagal[®]), both applied as foliar spray at 5 mL L⁻¹ and 0.1 mL L⁻¹, respectively, twice per week starting at 72 dat. Plants in the organic treatments were irrigated with 0.5 L of well water per plant during the first 30 dat. From transplant to harvest, an average of 1 L per plant was applied. In the conventional treatment (S3), the nutrient solution (Sánchez and Escalante, 1989) was applied via fertigation using the same irrigation schedule.

Experimental Design and Treatments

A randomized complete block design (RCBD) with a factorial arrangement was used in the greenhouse, considering three levels of the variety factor (MM, C-40, and Riñón) and three levels of substrate factor (S1: 40:60 T/V, S2: 50:50 T/V, and S3: unmixed T), resulting in nine treatments. Each treatment was replicated three times, with six plants per experimental unit. For the evaluation of fruit and seed quality, a single batch was formed from the harvested fruits collected for this purpose. Therefore, variables related to quality were analyzed using a completely randomized design with a factorial arrangement consisting of the same nine treatments, defined by the combination of the three substrate levels (S1, S2, and S3), each with its corresponding management, and the three tomato varieties evaluated.

Variables Evaluated

Throughout the growing season (120 dat), air temperature (°C) and relative humidity (%) inside the greenhouse were recorded every 30 min using a Hobo Onset[®] MX2301A sensor. Climatic variables were used to explain the results. Fruit yield per plant (FY) was determined by summing the weights of five fruits harvested at the ripening stage or when they were fully red. These fruits were randomly selected from the first to the fourth bunch. In addition, the following information was obtained from five other fruits from the fourth bunch: firmness (FF) at two opposite sites in the equatorial region using a Greenwich[®] FDV-30 texturometer; titratable acidity (TA) in 10 mL of juice; vitamin C (VITC) in 5 g of fruit, using the Tillman titration method; and total soluble solids (TSS) with an Atago[®] PAL-1 digital refractometer. To measure these last three variables, the AOAC (2005) methodology was followed. Fruit color was measured in a chamber illuminated with diffused light from

LED lamps. Digital images (610 × 813 pixels, JPG format) were captured from four sides of five fruits using a Canon[®] EOS Rebel T5 camera. The images were processed using PlantCV version 4.2.1 in Python 3.9, through the Jupyter Notebook web-based interface version 4.0.11. The CIE-LAB color model was used to segment the fruit and remove the background from each image. Average values and modes for each channel of the RGB, CIE-LAB, and HSV color models were then calculated. Seeds were extracted from 20 fruits from the fourth bunch, harvested at ripeness stage 6. The fermentation method was used to extract the seeds by hand. The fruit pulp and juice were left to ferment for 24 h. The seeds were then washed with running water, using a colander to remove mucilage residues. The clean seeds were left to dry on paper towels at room temperature (25 °C) for 7 d. Subsequently, a single batch was formed, enabling the analysis of variance for these variables to be performed using a completely randomized block design (CRBD). The seeds were then placed in paper envelopes and stored at room temperature for two months prior to use.

To assess physical seed quality, the weight of one thousand-seed weight (TSW) was measured following the standard procedure of ISTA (2021). Four replicates were used, each consisting of eight samples of 100 seeds. The seeds were weighed using a PA2202 balance (Ohaus[®]) with a precision of 0.001 g, and the average weight per replicate was multiplied by 10 to obtain the TSW. Hectoliter weight (HW) was estimated by measuring the volume displaced by 1 g of seeds in a 10 mL test tube. Seed length (SL) and width (SW) were measured using four replicates of 25 seeds each, through image processing with ImageJ[®] software version 1.54f. For this purpose, seeds were captured in a scanner HP[®] ScanJet 4890 at 600 dpi. To assess physiological seed quality, a germination test was conducted. Four replicates of 25 seeds each were sown in plastic boxes (11 × 11 × 3.5 cm) on filter paper moistened with distilled water. The boxes were placed in a germination chamber at 25 °C under constant light. After 14 d, the germination (G) percentage was determined following the ISTA (2021) criteria. Additionally, radicle emergence rate (RER) was evaluated through daily counts. At the end of the test, the radicle emergence rate index (radicles d⁻¹) was calculated, based on the resulting data, using Maguire's germination rate index (1962):

$$RER = \sum (ni / ti)$$

Where: *ni* = number of seedlings germinated in the time interval. *ti* = the time in days from sowing to the day of counting.

In order to assess seed vigor, an accelerated aging test was performed (Delgado-Vargas *et al.*, 2022). Four replicates of 25 seeds were placed in plastic boxes, which were then subjected to 45 °C and 100% relative humidity for 72 h in a Thelco 3480 conventional drying oven (Thermo Electron Corporation[®]). After this treatment, the seeds were sown, using a germination test similar to the one previously described, in which germination percentage (GAAA) and radicle emergence rate (RERA) were evaluated.

Data Analysis

Data were analyzed using R Studio version 3.6.4 for both DEBA and DECA designs. An analysis of variance (ANOVA) was conducted, followed by Tukey's HSD test at a significance level of $\alpha=0.05$. Percentage data were transformed using the arcsine square root transformation: $\arcsin\left(\sqrt{(X/100)}\right)$. If the color-related response variables did not meet the assumptions of normality, a Kruskal-Wallis test was applied, followed by Conover's post hoc pairwise multiple comparison test.

RESULTS AND DISCUSSION

Environmental Conditions

The recorded temperatures exceeded the optimal range for the crop, which is between 23 and 26 °C (Table 1). Growth and production of this species —classified by Delgado-Vargas *et al.* (2022) as sensitive to high temperatures— are reduced when exposed to temperatures above this range.

A low seed production was observed in the harvested fruits (a variable not measured), a situation likely attributable to adverse temperature conditions during anthesis of the first four bunches (from April 20 to July 5, 2023). During this period, the average temperature was 30.1 ± 2.9 °C and the average maximum temperature was 39 ± 3.5 °C —values that exceed the optimal range for this crop. Temperatures above 35 °C have a negative impact on pollination: they induce an elongation of the stigma that hinders contact between the pollen in the stamens and the stigma (Jarma-Orozco *et al.*, 2012). Although the average maximum relative humidity recorded in the morning ($60 \pm 20\%$) was adequate for pollination (Jarma-Orozco *et al.*, 2012), high temperatures may have contributed to the low seed set.

Fruit Yield and Quality

The ANOVA results revealed that the substrate factor (S) had a significant effect ($P \leq 0.05$) on fruit yield (FY). The variety factor (V) and the interaction between substrate and variety had a highly significant effect ($P \leq 0.01$). The highest FY was recorded with the S3 substrate, which outperformed the organic treatments; however, no significant differences were found between the organic treatments (Table 2). The complete and balanced nutrient solution provided improved nutrition. Similar results have been reported in tomato by De Grazia *et al.* (2007), Rodríguez *et al.* (2008) and Cruz *et al.* (2009).

Regarding the effect of the variety factor on FY, V1 recorded a higher yield than V2 and V3. The best treatment was the S3V1 interaction, which corresponded to the level with the

Table 1. Average and standard deviation (SD) of maximum, mean, and minimum air temperature (AT) and relative humidity (RH) recorded in the greenhouse during the growing cycle.

Variable	Maximum	SD	Mean	SD	Minimum	SD
AT (°C)	37.7	2.7	30.1	2.6	19.6	1.9
RH (%)	66.1	11.4	39.0	11.4	27.1	10.1

AT: air temperature. RH: relative humidity.

Table 2. Comparison of means for individual factors and their interaction on fruit-related variables in three tomato varieties grown under two organic production treatments and one conventional treatment.

SV	FY (kg plant ⁻¹)	FF (N)	TA (%)	VITC (mg 100 g ⁻¹)	TSS (° Brix)
S1	0.80 b	7.62 a	0.79 ab	3.0 a	6.50 a
S2	0.81 b	7.74 a	0.83 a	2.8 a	6.87 a
S3	1.46 a	5.09 b	0.69 b	2.7 a	5.75 b
LSD	0.65	1.50	0.007	-	0.72
V1	1.58 a	6.90 ab	0.59 c	2.0 c	5.85 b
V2	1.14 b	8.16 a	0.79 b	2.4 b	6.37 ab
V3	0.35 c	5.39 b	0.94 a	4.1 a	6.91 a
LSD	0.42	1.55	0.004	0.29	0.73
S1V1	1.25 c	7.05 bcd	0.65 d	2.43 d	6.25 b
S1V2	0.76 d	9.37 a	0.84 bc	2.77 c	6.60 ab
S1V3	0.25 e	6.45 cd	0.90 b	3.79 b	6.66 ab
S2V1	1.31 c	8.07 abc	0.65 d	1.96 ef	6.80 ab
S2V2	0.87 d	8.85 ab	0.81 c	2.27 de	6.39 b
S2V3	0.40 e	6.30 cd	1.04 a	4.42 a	7.43 a
S3V1	2.17 a	5.57 d	0.46 e	1.75 f	4.50 c
S3V2	1.79 b	6.27cd	0.72 d	2.29 de	6.12 b
S3V3	0.68 c	3.42 e	0.88 bc	4.33 a	6.63 ab
LSD	0.92	2.12	0.004	0.34	0.98

SV: source of variation; FY: fruit yield; FF: fruit firmness; TA: titratable acidity; VITC: vitamin C; TSS: total soluble solids; LSD: least significant difference. Means with the same letter in the same column are statistically equal (Tukey $\alpha=0.05$).

highest performance for each individual factor (Table 2). Of the three varieties studied, only V1 (Moneymaker) is the result of a plant breeding program in a scientific research center and has become a reference in agronomic and physiological research (Delgado-Vargas *et al.*, 2022). This may explain why the yield of Moneymaker yield is higher than that of the other two varieties, which were selected for different traits. On the one hand, genotype V2 (C-40), native to the state of Campeche, is resistant to high temperatures (Delgado-Vargas *et al.*, 2022). On the other hand, V3 (Riñón) was chosen due to its traditional use in organic production systems.

Regarding fruit quality, the substrate factor had a highly significant effect ($P \leq 0.01$) on fruit firmness (FF) and a significant effect ($P \leq 0.05$) on total soluble solids (TSS) and titratable acidity (TA). Nevertheless, it had no effect on vitamin C (VITC). The variety factor had a highly significant effect ($P \leq 0.01$) on FF, TA, and VITC, as well as a significant effect ($P \leq 0.05$) on TSS. The interaction between factors (substrate \times variety) had highly significant effect on all the variables studied.

S1 and S2 recorded higher FF and TSS values than substrate S3. S1 and S2 also ranked higher in titratable acidity (TA), although only S1 surpassed S3 (Table 2).

On the one hand, Zahedi *et al.* (2010) indicated that the fulvic and humic acids found in the vermicompost used in treatments S1 and S2 likely contributed significant amounts of Ca—an essential element for the regulation of the physical properties of the fruit. Ca increases fruit size and promotes uniformity, elasticity, hydration, and skin firmness. It also improves postharvest fruit performance and promotes sugar formation, resulting in an increase of the °Brix index. Furthermore, Batu (2004) proved that Ca supplementation helps to minimize pectin decomposition and maintains the firmness of the pectic matrix, which supports the strength of the fruit walls.

On the other hand, the firmness values for all treatments were higher than those reported by Batu (2004) for 100% marketable fruits produced without Ca deficiency. Therefore, the type of Ca input in S1 and S2 enabled a sufficient assimilation. However, this was not the case for the hydroponic treatment, where Ca absorption may have been affected by the greenhouse environmental conditions and the lower moisture retention of the substrate composed solely of tezontle.

Variety 3 (Riñon) stood out in TA, VITC, and TSS; it also had the lowest FF (Table 2). Native varieties (including V3) are usually considered to have better flavor than improved varieties. For example, Juárez-López *et al.* (2009) reported a TA value of 1.01% for a native tomato variety, a result similar to that found in this study for V3 grown in S2 (Table 3). Furthermore, the TA values observed in V2 and V3 (both native varieties) exceeded the 0.4-0.6% range reported by Nuez (1995) for commercial tomatoes. However, these values were comparable to those observed for V1 in the present study.

Regarding the effect of substrate on fruit color, no significant differences were found in luminosity (CIE-L), red intensity (positive CIE-a*), yellow intensity (positive CIE-b*), hue, or chroma. However, the variety factor and its interaction with the substrate caused significant differences in the fruit color variables (Table 3).

Table 3. Post hoc pairwise multiple comparison (Conover's test) of the medians for the CIE-Lab color space channels, hue, and chroma of tomato fruits, as affected by the interaction between substrate and variety.

VS	CIE-L	CIE-a*	CIE-b*	Matiz
S1V1	28 b	40 a	30 a	5.5 a
S1V2	28 b	37 b	19 b	351.5 a
S1V3	23 d	32 c	16 c	353.5 a
S2V1	27 b	38 b	30 a	7 a
S2V2	26 c	38 b	19 b	356 a
S2V3	24 d	32 c	15 c	354 a
S3V1	28 b	37 b	31 a	7 a
S3V2	31 a	40 a	19 b	355 a
S3V3	23 d	32 c	16 c	356 a
LSD	4	3	12	355

VS: variation source. CIE-L: luminosity; CIE-a*: a positive value indicates a reddish tint; CIE-b*: a positive value indicates a yellowish tint. LSD: least significant difference. Medians with the same letter in the same column are statistically equal ($\alpha=0.05$).

The Moneymaker (V1) variety had high luminosity and a red color with strong yellow hues. Its coloration was an intense, highly saturated red, contributing to a vibrant color. The native Campeche 40 variety (C40) also showed high luminosity, but displayed a red color with lighter yellow hues. Its lower color saturation, compared to Moneymaker, resulted in lighter red fruits. Variety 3 (Riñón) was characterized by lower luminosity and saturation, producing fruits with a light red color and pale-yellow hues, which gave them an overall orange appearance.

The combination of a tezontle-based substrate with particles smaller than 5 mm and hydroponic management, along with the C-40 variety, produced fruits with the highest luminosity. In contrast, the Riñón variety, cultivated under organic management, consistently exhibited the lowest luminosity and the lowest red intensity, regardless of the substrate. The most intense red coloration was observed in the Moneymaker variety grown in the 40:60 tezontle/organic vermiculite mix (S1V1), as well as in the C-40 variety under hydroponic conditions (S3V2). The Moneymaker variety also recorded the highest yellow values and the greatest chroma, regardless of the substrate.

Regarding fruit yield and quality, González-Fuentes *et al.* (2021) consider that organic nutrition does not necessarily result in higher yields compared to conventional nutrition. However, it does lead to higher-quality fruits, with growth and morphological characteristics that are similar to or better than those obtained with inorganic nutrition. These findings are consistent with the results of the present experiment.

Seed Quality

In terms of the physical seed quality variables, the substrate factor showed a highly significant effect ($P \leq 0.01$) on seed length (SL), seed width (SW), and thousand-seed weight (TSW). No substrate effect was observed on volumetric weight (VW). The variety factor only had a highly significant effect on SL. Meanwhile, the interaction between substrate and variety had a highly significant effect on all four variables evaluated. The means test showed that S2- and S3-levels of the substrate factor produced higher SL, SW, and TSW values than S1, although there were no statistical differences between S1 and S3 in the case of SL (Table 4). The TSW, SL, and SW values for the Moneymaker (V1) and C-40 (V2) varieties were similar to those reported by Delgado-Vargas *et al.* (2022), who studied the effect of high temperature on the seed quality of both varieties.

In the interaction between factors (substrate \times variety), the S2V2 treatment produced longer and wider seeds, being similar to S1V1 in the first variable and to S3V3 in the second. The highest TSW and VW values resulted from treatments S3V2 and S3V1 (similar to S3V3). Because some treatments resulted in bigger (longer or wider) seeds with the same weight, their accumulated reserves may be lower (Taylor, 2020). Furthermore, thickness—a third dimensional variable related to seed size which could have influenced TSW and VW values—was not measured.

Regarding seed physiological quality, the substrate factor (S) had a significant effect ($P \leq 0.05$) on germination (G), germination after accelerated aging (GAAA), and radicle emergence rate (RER) of artificially aged seeds. However, it had no effect on the emergence rate of unaged seeds (RUS). The variety factor (V) generated highly significant differences

Table 4. Comparison of means using Tukey's test for each independent factor and their interaction, based on seed quality variables from three tomato varieties grown under two organic and one conventional production treatments.

SV	SL (mm)	SW (mm)	TSW (g)	VW (kg hL ⁻¹)	G (%)	RER (Rad d ⁻¹)	GAAA (%)	RERA (Rad d ⁻¹)
S1	3.58 b	2.44 b	2.63 b	20.16 a	80 b	3.77 a	52 b	2.05 b
S2	3.76 a	2.61 a	2.95 a	21.37 a	92 a	4.32 a	76 a	2.90 a
S3	3.68 ab	2.58 a	3.00 a	21.86 a	95 a	5.33 a	83 a	3.25 a
LSD	0.13	0.72	0.05	1.58	10	1.3	0.21	0.93
V1	3.74 a	2.54 a	2.81 a	21.54 a	91 a	3.68 b	72 b	2.45 b
V2	3.73 a	2.53 a	2.90 a	21.23 a	98 a	7.05 a	90 a	4.06 a
V3	3.54 b	2.58 a	2.86 a	20.62 a	67 b	2.60 c	50 c	1.69 c
LSD	0.12	0.03	0.06	0.62	23	3.8	0.18	0.56
S1V1	3.83 ab	2.52 c	2.6 e	20.55 d	80 b	3.02 d	48 c	1.75 d
S1V2	3.53 e	2.35 d	2.7 d	20.40 d	97 a	6.20 b	92 a	3.95 a
S1V3	3.37 f	2.45 c	2.6 e	19.52 e	56 d	2.10 e	17 d	0.50 e
S2V1	3.79 b	2.59 b	2.8 c	20.86 d	95 a	3.45 d	82 ab	2.75 bc
S2V2	3.90 a	2.66 a	2.8 c	21.60 c	100 a	6.77 b	88 a	3.80 a
S2V3	3.58 de	2.59 b	2.9 b	20.72 d	67 c	2.75 de	59 c	2.15 cd
S3V1	3.60 de	2.46 c	3.0 a	22.27 ab	99 a	4.57 c	85 ab	2.87 b
S3V2	3.75 bc	2.59 b	3.0 a	22.52 a	99 a	8.17 a	91 a	4.45 a
S3V3	3.68 cd	2.71 a	2.9 b	21.71 bc	79 b	2.95 de	74 b	2.45 bcd
LSD	0.10	0.07	0.04	0.56	16	5.4	0.15	0.44

SV: source of variation; SL: seed length; SW: seed width; TSW: thousand-seed weight; VW: volumetric weight; G: germination; RER: = radicle (Rad) emergence rate; GAAA: germination after accelerated aging; RERA: radicle (Rad) emergence rate after accelerated aging; LSD: least significant difference. Means with the same letter in the same column are statistically equal (α , 0.5).

($P \leq 0.01$) in RER, GAAA and RERA, and significant differences in G ($P \leq 0.05$). Finally, the $S \times V$ interaction caused highly significant differences in all variables. A seed of high physiological quality is considered to have better germination (higher percentage and speed) and vigor (greater resistance to storage under adverse conditions, such as accelerated aging) (Delgado-Vargas *et al.*, 2022). Furthermore, accelerated aging is used to test vigor —*i.e.*, the ability of seeds to germinate quickly and establish successfully, especially under adverse conditions (ISTA, 2021).

Similarly, for most of the seed physical variables, substrate levels S2 and S3 resulted in better values for G, GAAA, and RERA values than S1 (Table 4). Among the varieties, V2 showed superior values in G, GAAA, and RERA compared to the other two varieties. In the case of G, both V1 and V2 were better than V3. Regarding the interaction effect, the most notable result is that treatment S1V2 is in the top group for G, GAAA, and RERA. This is attributed to the strong influence of variety (V2), which compensated for the lower performance of substrate S1, the treatment with the lowest values for these variables (Table 4). The literature reviewed did not report data on tomato seed yield or quality under organic production systems, highlighting the relevance of the present findings. Overall, substrate S2 produced seeds with physical and physiological quality comparable to those from S3, which was managed conventionally and it is considered

optimal for tomato cultivation. According to Alcántar-González and Trejo-Téllez (2013), high nitrogen concentrations (>120 ppm) promote vigorous growth, increased flower production, and higher seed yield. This may help explain the observed results. Since S2 and S3 had seeds with similar physical and physiological quality characteristics, S2 can be recommended for tomato seed production under organic management systems.

CONCLUSIONS

Treatments with organic substrates S1 and S2 resulted in higher fruit quality than treatment S3 (conventional production), as indicated by greater firmness and higher total soluble solids. Substrate S2, a 50:50 (v/v) mixture of vermicompost and tezontle, also produced the highest titratable acidity. Although neither organic nor conventional substrates significantly affected fruit color, the C-40 variety (V2) grown under the conventional treatment (S3) exhibited the highest luminosity. In contrast, the Riñon variety, used in organic production, consistently showed the lowest luminosity and red intensity, regardless of substrate. The most intense red coloration was observed in fruits from the Moneymaker variety (V1) combined with organic substrate S1 and from the C-40 variety (V2) under conventional treatment S3. The highest fruit yield was recorded under the conventionally managed treatment S3. Both S3 and the organic managed S2 treatments produced the highest seed quality, based on seed length, seed width, thousand-seed weight, germination, germination after accelerated aging, and radicle emergence rate after accelerated aging. Since treatment S2 stood out in both fruit and seed quality traits, this mixture could be recommended for use in commercial organic tomato production.

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