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RESEARCH PAPER

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FERTILIZATION-DRIVEN CHANGES IN BIOCHEMICAL PROFILE AND STORAGE STABILITY OF DRIED TOMATOES

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ABSTRACT

This study evaluated the effects of different fertilization strategies on the biochemical composition and storage stability of dried tomatoes. Tomatoes were grown under ten fertilization treatments and analyzed in two periods: immediately after drying (Period 1) and after six months of storage (Period 2). Total phenolic content (TPC), antioxidant capacity, and organic acid composition (oxalic, citric, malic, succinic, and fumaric acids) were determined. Fertilization treatment, drying period, and their interaction significantly affected TPC and organic acid composition ($p < 0.0001$). Antioxidant capacity was significantly influenced by fertilization and drying period ($p < 0.05$). In Period 1, TPC values ranged from approximately 31.40 to 35.96 mg GAE g^{-1}, while antioxidant capacity varied between 175.69 and 373.38 Trolox µmol TE g^{-1}, depending on fertilization treatment. After six months of storage (Period 2), both TPC (32.14–40.86 mg GAE g^{-1}) and antioxidant capacity (563.19–781.25 Trolox µmol TE g^{-1}) generally increased. Heatmap analyses revealed distinct clustering patterns between periods, with a more coherent association among malic acid, succinic acid, and TPC observed in Period 2. These findings indicate that fertilization strategies strongly influence both the initial biochemical composition and the long-term stability of dried tomatoes.

Keywords: dried tomato, fertilization strategy, antioxidant capacity, organic acids

INTRODUCTION

Tomato (*Solanum lycopersicum* L.) is one of the most widely cultivated and consumed vegetables worldwide, not only for its culinary value but also for its rich composition of bioactive compounds, such as phenolic substances and antioxidants, which are associated with human health benefits. Phenolic compounds in tomatoes are important contributors to antioxidant capacity and are influenced by both genetic and environmental factors as well as cultivation practices. Studies have shown that phenolic content and antioxidant activity can vary significantly across tomato varieties and cultivation methods, with organic and fertilization regimes playing a key role in modulating these traits [Perea-Domínguez et al. 2018].

Fertilization management, including the type and rate of nutrient application, has been demonstrated to affect the accumulation of phenolic compounds and other quality parameters in tomatoes. For example, tomatoes fertigated with different nitrogen levels exhibited variations in total phenolic content and antioxidant capacity, indicating that nutrient supply influences secondary metabolite synthesis in fruit tissues [Jorge et al. 2017]. Moreover, differentiated organic fertilization strategies have been reported to affect phenolic composition and antioxidant potential across tomato varieties, suggesting that both nitrogen and carbon availability can alter the profile of bioactive molecules [González-Coria et al. 2022].

In addition to fertilization, post-harvest processes such as drying and storage can significantly alter the biochemical composition of tomato products. Drying is widely used to extend shelf life and concentrate nutrients;

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however, it also induces structural and metabolic changes that influence the stability and extractability of bioactive compounds. Recent studies have demonstrated that drying treatments can significantly affect the global metabolome and health-related compounds in tomatoes, leading to variations in phenolic content, organic acids, and antioxidant capacity [Bakir et al. 2023]. Furthermore, different drying conditions and processing parameters have been shown to influence the retention and degradation of bioactive compounds and structural properties of tomatoes [Fterich et al. 2023, Bayana et al. 2024]. In addition, comprehensive reviews have emphasized that advances in drying technologies play a critical role in determining the stability and functional quality of plant-based products, including tomatoes [Belwal et al. 2022].

Previous studies have shown that storage can influence the phenolic composition and antioxidant capacity of processed tomato products, although the direction and magnitude of these changes depend on product type and processing conditions. While reductions in phenolic content have frequently been reported for liquid tomato products such as juices and sauces during storage, dried tomato products often exhibit different behavior due to their low water activity and reduced enzymatic activity. In dried matrices, phenolic compounds may remain relatively stable or become more extractable over time, resulting in variable antioxidant responses during storage [Dewanto et al. 2002, Chang et al. 2006].

Despite the increasing number of studies on drying technologies and fertilization practices, limited information is available regarding their combined effects on the biochemical stability of dried tomatoes during storage. In particular, the interaction between pre-harvest fertilization strategies and post-harvest metabolic changes remains insufficiently understood.

In this study, it was hypothesized that different pre-harvest fertilization strategies (chemical, vermicompost, and organomineral) would not only determine the initial biochemical profile of dried tomatoes immediately after drying, but also significantly modify the metabolic reorganization and biochemical stability processes occurring during six months of storage. Specifically, it is anticipated that different nutrient source combinations will have a decisive impact on the dynamic changes (accumulation or reduction) of organic acids during storage, as well as on the long-term preservation of phenolic compounds and antioxidant capacity.

MATERIAL AND METHODS

Field experimental design

Seedlings of the Nergis F1 tomato cultivar were used as plant material for the experiment. The study was conducted in 30 plots arranged according to a randomized complete block design with three replications. Each plot was separated by a 1-m buffer zone, while blocks were spaced 2 m apart. The field trial was carried out under open-field conditions at Van Yüzüncü Yıl University, Turkey (38°34'25"N, 43°17'40"E). The experimental layout and field views of the study are presented in Figure 1.

Transplanting was performed on 11 June 2021 using a spacing of 100 cm between rows and 50 cm between plants within rows, resulting in a total of 600 plants, with 20 tomato seedlings assigned to each plot. To minimize border effects, six centrally located plants in each plot were selected for sampling and permanently tagged at the early flowering stage to ensure uniformity in fruit selection.

Tomato fruits were harvested at the red-ripening stage from the mid-canopy region of the tagged plants to reduce variation related to fruit position and light exposure. Only fruits that were uniform in size and maturity and free from visible defects were included in the analyses, ensuring a standardized and unbiased sampling procedure for all biochemical and quality measurements.

Pre-plant soil analysis indicated that the experimental site had slightly alkaline soil (pH 7.83), low organic matter content (0.93%), high lime content (10.84%), and an electrical conductivity of 0.01%, indicating no salinity problems. Throughout the growing season, plants were irrigated using a drip irrigation system to maintain consistent soil moisture. Detailed soil characteristics and climatic conditions during the 2021 growing season are presented in Tables 1 and 2, respectively.

Fertilization program

The fertilizer treatments were established to represent practical nutrient management approaches commonly used to improve both crop performance and soil quality. The different ratios of chemical fertilizer (CF), orga-

Figure 1. Experimental layout and field views of the study

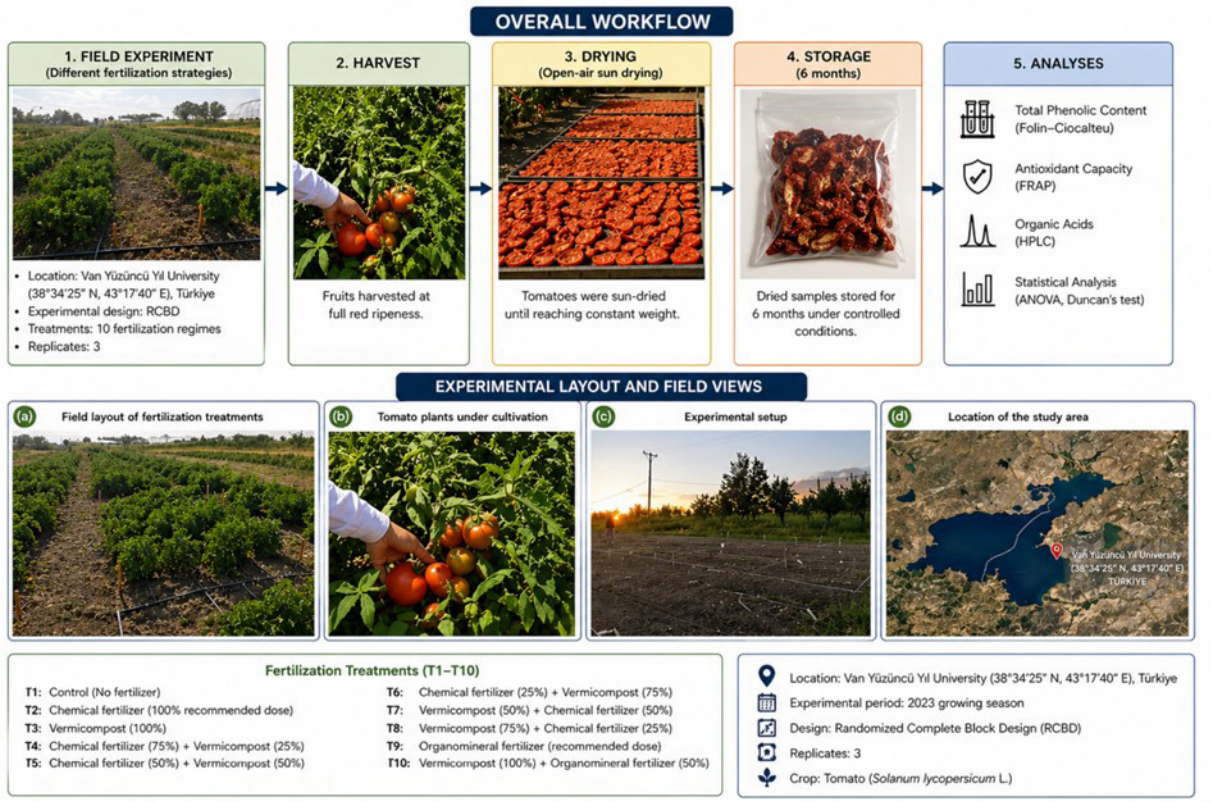


Table 1. Soil properties of the experimental site

Parameter	Value
P (mg kg^{-1})	5.50
K (mg kg^{-1})	11.04
Organic matter (%)	0.93
Lime (%)	10.84
pH (%)	7.83
Electrical conductivity/salt (%)	0.01
Structure (%)	sand: 37, clay: 24.3, silt: 38.6
N (%)	0.17
Mn (mg kg^{-1})	0.98
Na (mg kg^{-1})	86.35
Fe (mg kg^{-1})	1.12
Cu (mg kg^{-1})	0.53
Zn (mg kg^{-1})	0.46
Ca (mg kg^{-1})	1025
Mg (mg kg^{-1})	134

Table 2. Climatic conditions during the 2021 growing season

Parameter	May	June	July	August	September
Average temperature (°C)	19.2	21.1	24.5	26.4	22.8
Minimum temperature (°C)	10.5	14.3	17.1	19.6	16.5
Maximum temperature (°C)	27.8	27.9	31.8	33.2	29.1
Sunshine duration (h)	11.9	12.7	12.5	12.6	11.8
Precipitation (mm)	8.1	14.7	12.7	15.5	1.1
Wind (m s^{-1})	3.1	2.7	2.1	2.3	2.1
Relative humidity (%)	41.8	48.3	34.2	30.9	35.8
Evaporation (mm)	65.2	188.5	199.4	213.4	25.0

no-mineral (OMF), and vermicompost (VC) were selected to take advantage of their complementary nutrient contributions. Chemical fertilizers supplying readily available nutrients, while vermicompost and organo-mineral fertilizers support longer-term improvements in soil organic matter content and microbial activity. This integrated approach aligns with sustainable agriculture principles by enhancing nutrient-use efficiency and reducing potential environmental impacts, which is particularly relevant for regions challenged by soil degradation and rising agricultural input costs.

Table 3. Composition of the fertilizers used during plant growth

Chemical fertilizer (CF) (20:20:20) (%)	Triple super phosphate (TSP)	46% nitrogen fertilizer	Organomineral fertilizer (OMF) 11:11:11 (%)	Vermicompost (VC) (%)
Total nitrogen: 20 Ammonium nitrogen: 3.9 Nitrate nitrogen: 5.9 Urea (N-NH_2): 10.2 Water soluble phosphorus pentoxide: 20 Water soluble potassium oxide: 20 Water soluble iron: 0.05 Water soluble copper: 0.02 Water soluble zinc: 0.02 Water soluble manganese: 0.02	Water soluble phosphorus pentoxide: 39 Phosphorus pentoxide soluble in neutral ammonium citrate (P_2O_5): 42	Urea: 46	Organic matter: 18.00 Total nitrogen: 11.00 Ammonium nitrogen: 5.00 Urea nitrogen: 6.00 Water soluble potassium oxide: 11.00 Total phosphorus pentoxide: 11.00 Water soluble phosphorus pentoxide: 9.00 Water soluble sulfur trioxide: 7.00 Total sulfur trioxide: 11.00 Total zinc: 0.10 Total humic acid + fulvic acid: 5.00	Organic matter: 35.00 Total nitrogen: 2.00 Organic nitrogen: 1.00 Water soluble potassium oxide: 2.00 Total phosphorus pentoxide: 0.40 Total humic acid + fulvic acid: 20.00 C/N: 10.04 Max. EC (dS m^{-1}): 2.00 Max. moisture: 35.00 pH: 6–8

C/N – carbon-to-nitrogen ratio, EC – electrical conductivity

Table 4. Fertilizer application rates used during the plant growing period

Treatment	Fertilizer combinations	Fertilizer doses
T1	control	–
T2	$CF_{(\%100)}$	19.8 kg da^{-1} N:P:K (20:20:20) + 14.21 kg da^{-1} TSP + 23.63 kg da^{-1} 46% urea
T3	$VC_{(\%100)}$	741.5 kg da^{-1}
T4	$OMF_{(\%100)}$	134.82 kg da^{-1}
T5	$CF_{(\%25)}$ + $VC_{(\%75)}$	4.75 kg da^{-1} N:P:K (20:20:20) + 3.55 kg da^{-1} TSP + 5.91 kg da^{-1} 46% urea + 556.13 kg da^{-1} VC
T6	$CF_{(\%50)}$ + $VC_{(\%50)}$	9.9 kg da^{-1} N:P:K (20:20:20) + 7.11 kg da^{-1} TSP + 11.82 kg da^{-1} 46% urea + 370.75 kg da^{-1} VC
T7	$CF_{(\%75)}$+$VC_{(\%25)}$	14.85 kg da^{-1} N:P:K (20:20:20) + 10.66 kg da^{-1} TSP + 17.73 kg da^{-1} 46% urea + 185.38 kg da^{-1} VC
T8	$OMF_{(\%25)}$ +$VC_{(\%75)}$	33.71 kg da^{-1} OMF + 556.13 kg da^{-1} VC
T9	$OMF_{(\%50)}$ + $VC_{(\%50)}$	67.41 kg da^{-1} OMF + 370.75 kg da^{-1} VC
T10	$OMF_{(\%75)}$ + $VC_{(\%25)}$	101.12 kg da^{-1} OMF + 185.38 kg da^{-1} VC

CF – chemical fertilizer, VC – vermicompost, OMF – organo-mineral fertilizer, N:P:K – nitrogen:phosphorus:potassium, TSP – triple super phosphate

The experiment included three main fertilizer sources: chemical fertilizer supplied by Gübretaş, vermicompost sourced from Yaşa Tarım, and organo-mineral fertilizer produced by Hektaş (Table 3). These inputs were blended in different proportions to generate ten fertilizer treatments, as outlined in Table 4. Throughout the growing period, urea applications were made twice approximately four weeks apart to boost nitrogen supply in treatments receiving chemical fertilizer alone or in combination.

Drying procedure

Tomatoes harvested at the red-ripening stage were used as plant material in the study. Fruits were visually inspected, and those with uniform size and free from physical damage or defects were selected for further analysis. Selected samples were gently washed with distilled water to remove surface impurities and allowed to dry at room conditions. After preparation, tomatoes were sliced uniformly and arranged in a single layer on drying surfaces. Drying was carried out under natural sun-drying conditions by exposing the samples directly to sunlight under ambient environmental conditions. During the drying period, the average daytime temperature ranged between approximately 25–35 °C, and relative humidity ranged between 30–50%. The drying process lasted approximately 5–7 days, depending on environmental conditions. Samples were exposed to natural air circulation throughout the drying period. The drying process was monitored periodically and continued until constant weight was achieved. Following drying, samples were cooled to room temperature and stored in airtight containers protected from light. Samples analyzed immediately after drying were defined as Period 1 (P1), while the remaining samples were stored under ambient conditions (approximately 20–25 °C and 40–60% relative humidity) for six months with limited oxygen exposure due to sealed storage conditions, and subsequently analyzed as Period 2 (P2). A storage period of six months was selected to represent a typical long-term storage duration under ambient conditions, allowing sufficient time for biochemical transformations, stabilization of metabolites, and assessment of storage-related changes in dried tomato quality.

Extraction and HPLC–DAD determination of organic acids

Organic acids were determined following a modified protocol based on Bevilacqua and Califano [1989], adapted specifically for tomato tissue. Four fresh tomato fruits were homogenized, and 1 g of the homogenate was extracted with 20 mL of 0.009 N sulfuric acid (H_2SO_4). The mixture was homogenized thoroughly and shaken for 1 hour to facilitate extraction, then centrifuged at 15,000 rpm for 15 minutes. The supernatant was clarified through sequential filtration using coarse filter paper, a 0.45 µm membrane, and a SEP-PAK C18 cartridge to remove particulate matter and impurities.

Analysis was performed on an Agilent 1100 HPLC system equipped with an Aminex HPX-87H column, with detection carried out by a diode-array detector at 214 and 280 nm. Organic acid concentrations were quantified by comparison with external standards prepared under the same chromatographic conditions, ensuring accurate and reproducible measurements.

Total antioxidant capacity (TAC) and total phenol (TP)

Total phenols (TP) and total antioxidant capacity (TAC) were measured following the methods of Swain and Hillis [1959], and Benzie and Strain [1996], respectively. For TP, 150 µL of sample was reacted with Folin–Ciocâlteu reagent and sodium carbonate, incubated for 60 min, and absorbance was measured at 760 nm using a UV–Vis spectrophotometer (Genesys 10S, Thermo Fisher Scientific, USA). Results were expressed as gallic acid equivalents (GAE/100 mg FW). TAC was determined using the ferric reducing antioxidant power (FRAP) assay. Briefly, 150 µL of sample was mixed with FRAP reagent, incubated for 30 min, and absorbance was measured at 593 nm using a UV–Vis spectrophotometer mentioned above. Results were expressed as Trolox equivalents (TE/100 mg FW).

Statistical analysis

All experimental data were subjected to statistical analysis using a factorial experimental design. The effects of fertilization treatment (F), post-drying period (P), and their interaction (F × P) on organic acid composition, total phenolic content, and antioxidant capacity of dried tomato samples were evaluated. Data were analyzed by two-way analysis of variance (ANOVA), followed by Duncan's multiple range test, using IBM SPSS Statistics software (Version 26, IBM Corp., Armonk, NY, USA) to determine the significance of main effects and interaction terms. Results are presented as mean ± standard deviation.

RESULTS AND DISCUSSION

Fertilization treatments (F), post-drying period (P), and their interaction (F × P) had a highly significant effect on organic acid composition, total phenolic content, and antioxidant capacity ($p < 0.0001$), indicating that both pre-harvest nutrient management and post-drying processes jointly regulate the biochemical profile of dried tomatoes (Tables 5 and 6).

Table 5. Organic acid (μg g^{-1}) profile, total phenolics (mg GAE 100 g^{-1}), and antioxidant capacity (Trolox μmol TE g^{-1}) of dried tomatoes as affected by fertilization and storage period

Period	Treatment	Organic acid					Antioxidant capacity	Total phenolics
		oxalic	citric	malic	succinic	fumaric		
P1	T1	331.02 ±14.86de	3406.95 ±265.21a	38334.41 ±2595.44g	86936.92 ±4744.53j	1659.83 ±199.55d	233.57 ±29.87cd	35.96 ±1.11c
	T2	315.94 ±0.97f–h	3542.23 ±34.24a	35548.05 ±2797.66g–ı	85236.91 ±666.54j	1503.53 ±87.87d	213.66 ±7.90cd	33.19 ±2.03d–g
	T3	332.53 ±15.78de	2968.52 ±865.50ab	32866.42 ±6445.09ı–k	85131.72 ±4879.21j	1449.66 ±3.36d	210.42 ±36.32cd	32.83 ±1.33e–g
	T4	299.75 ±1.94ıj	3099.55 ±96.33ab	35679.99 ±3160.32g–ı	75100.84 ±1689.06k	1751.99 ±185.55d	373.38 ±252.19c	32.60 ±0.67fg
	T5	293.89 ±0.50j	3074.18 ±81.56ab	39163.68 ±3271.55g	93588.20 ±1334.19ı	1883.72 ±184.47cd	178.94 ±45.16d	31.40 ±1.19g
	T6	303.04 ±12.86h–j	2663.86 ±754.07bc	30126.40 ±3904.22jk	65827.56 ±4801.94l	1472.21 ±178.36d	217.82 ±9.45cd	32.95 ±1.31e–g
	T7	307.70 ±17.32g–j	2371.72 ±839.10c	28739.14 ±4926.29k	69373.44 ±6385.16l	1505.16 ±196.02d	175.69 ±52.21d	34.01 ±1.04d–f
	T8	590.48 ±1.09a	119.83 ±0.51d	37648.24 ±86.36gh	88616.08 ±135.82j	1890.64 ±14.18cd	194.68 ±48.93d	31.59 ±1.18g
	T9	602.05 ±4.22a	68.26 ±4.87d	34638.14 ±314.73g–j	77662.47 ±1247.14k	1747.57 ±6.19d	259.03 ±58.55cd	34.94 ±1.20cd
	T10	320.71 ±17.01e–g	3168.80 ±27.08ab	32987.27 ±638.96h–k	76078.37 ±743.57k	1533.75 ±80.90d	235.42 ±6.37cd	33.25 ±0.20d–g
P2	T1	386.92 ±3.49b	351.23 ±4.69d	79369.46 ±1465.03b	206615.53 ±2534.66bc	5966.84 ±603.28a	712.50 ±93.03ab	38.01 ±0.46b
	T2	325.67 ±0.23ef	419.68 ±0.95d	75695.07 ±243.35bc	203046.91 ±144.90c	2851.52 ±15.63b	611.81 ±36.14b	38.50 ±0.18b
	T3	178.22 ±1.26k	369.47 ±0.81d	78913.86 ±231.04b	231026.30 ±640.75a	2913.95 ±26.44b	591.67 ±142.92b	40.82 ±0.86a
	T4	389.31 ±7.12b	144.87 ±1.49d	83588.05 ±2259.11a	164542.54 ±3879.87f	5565.52 ±1119.03a	781.25 ±93.20a	39.01 ±1.48b
	T5	315.86 ±2.82f–h	432.93 ±5.41d	73412.26 ±773.23cd	197062.19 ±1561.15d	3268.35 ±963.34b	600.69 ±44.70b	40.86 ±0.31a
	T6	313.97 ±2.39f–ı	321.65 ±2.04d	69587.89 ±713.37d	192149.08 ±1738.29e	2750.54 ±56.15b	595.83 ±39.11b	38.60 ±0.41b
	T7	311.87 ±4.86f–ı	444.64 ±1.26d	75124.45 ±1573.87bc	208089.16 ±254.33b	3268.31 ±1044.96b	563.19 ±66.97b	38.05 ±0.71b
	T8	365.38 ±1.21c	156.19 ±0.12d	45273.73 ±498.37f	138969.21 ±893.84h	1364.06 ±128.65d	637.50 ±140.41ab	36.26 ±0.70c
	T9	393.59 ±0.55b	153.61 ±0.38d	50126.30 ±63.85e	150567.11 ±119.55g	2602.15 ±27.71bc	720.83 ±109.57ab	34.70 ±0.98c–e
	T10	345.06 ±2.05d	159.65 ±0.48d	44145.60 ±1421.86f	135012.90 ±1831.69h	1417.83 ±219.09d	597.22 ±55.55b	32.14 ±1.32fg

Different lowercase letters within the same column indicate statistically significant differences (Duncan's multiple range test, $p < 0.05$).

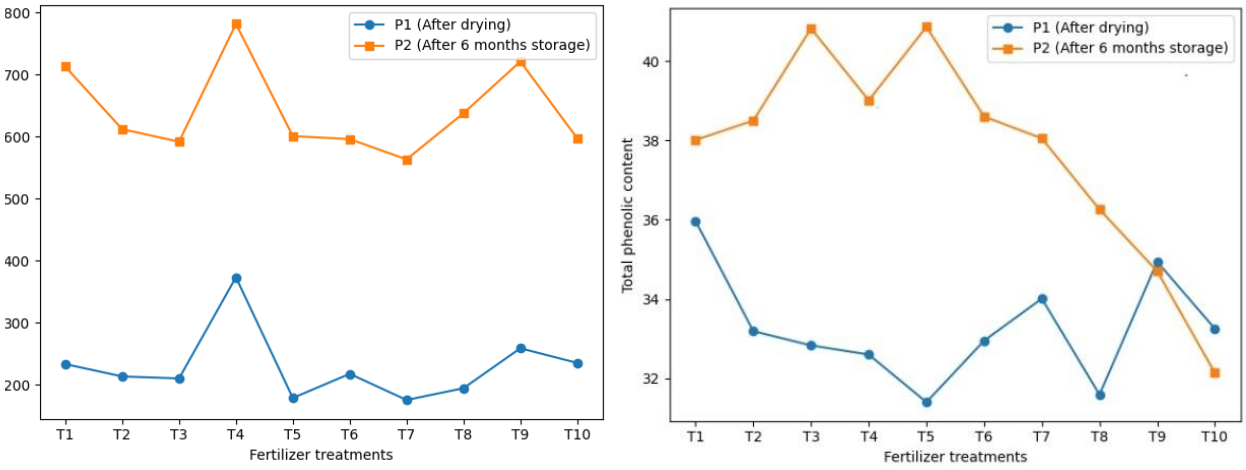
Table 6. Mean effects of fertilization treatments and storage period on the organic acid profile (μg g^{-1}), total phenolic content (mg GAE 100 g^{-1}), and antioxidant capacity (Trolox μmol TE g^{-1}) of dried tomatoes

Treatment	Organic acid					Antioxidant	Total phenolics
	oxalic	citric	malic	succinic	fumaric		
T1	358.97 ±32.10c	1879.09 ±1682.08ab	58851.94 ±22554.72ab	146776.23 ±65638.90b	3813.33 ±2393.04a	473.03 ±269.51ab	36.98 ±1.36a
T2	320.80 ±5.36f	1980.96 ±1710.42a	55621.56 ±22061.04c	144141.91 ±64528.64b	2177.53 ±740.48b	412.73 ±219.33b	35.85 ±3.18ab
T3	255.37 ±81.11h	1668.99 ±1525.18a–c	55890.14 ±25548.91bc	158079.01 ±79970.34a	2181.80 ±802.20b	401.04 ±228.70b	36.82 ±4.49a
T4	344.53 ±49.28d	1622.21 ±1619.49a–c	59634.02 ±26355.10a	119821.69 ±49062.29e	3658.76 ±2208.52a	577.32 ±280.76a	35.81 ±3.65ab
T5	304.88 ±12.17g	1753.55 ±1447.59a–c	56287.97 ±18878.83bc	145325.20 ±56689.92b	2576.04 ±979.78b	389.82 ±234.48b	36.13 ±5.23ab
T6	308.51 ±10.22g	1492.75 ±1368.66bc	49857.15 ±21759.21d	128988.32 ±69264.50d	2111.38 ±710.08bc	406.83 ±208.60b	35.77 ±3.22ab
T7	309.79 ±11.61g	1408.18 ±1181.41c	51931.79 ±25615.96d	138731.30 ±76085.14c	2386.74 ±1176.75b	369.44 ±218.93b	36.03 ±2.35ab
T8	477.93 ±123.30b	138.01 ±19.92d	41460.98 ±4188.89ef	113792.64 ±27585.47f	1627.35 ±299.81cd	416.09 ±260.14b	33.93 ±2.70c
T9	497.82 ±114.21a	110.93 ±46.85d	42382.22 ±8485.64e	114114.79 ±39939.37f	2174.86 ±468.42b	489.93 ±264.86ab	34.82 ±0.99bc
T10	332.88 ±17.19e	1664.23 ±1648.27a–c	38566.43 ±6190.68f	105545.64 ±32303.97g	1475.79 ±160.78d	416.32 ±201.30b	32.70 ±1.04d
Mean periods							
Period 1	369.71 ±116.26A	2448.39 ±1297.21A	34573.17 ±4362.53B	80355.25 ±9076.43B	1639.81 ±200.32B	229.26 ±91.03B	33.27 ±1.68B
Period 2	332.58 ±61.13B	295.39 ±123.12B	67523.67 ±14543.68A	182708.09 ±31890.88A	3196.91 ±1543.85A	641.25 ±102.06A	37.69 ±2.69A
P values							
Fertilization (F)	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.010	<0.0001
Period (P)	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
F × P	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	0.976	<0.0001

The significant interaction effect further demonstrates that temporal changes in biochemical parameters are strongly dependent on fertilization strategy rather than being uniform across treatments. Organic acids exhibited compound-specific responses during the post-drying period, reflecting differences in their metabolic roles. Oxalic acid decreased after drying, although the magnitude of reduction varied among treatments, suggesting that its behavior is governed by both degradation processes and fertilization-dependent metabolic regulation. This indicates that post-drying changes in oxalic acid cannot be explained solely by time, but are closely linked to pre-harvest nutrient status. Citric acid showed a pronounced decline from Period 1 to Period 2, indicating high sensitivity to post-drying processes (Tables 5–6). The reduction in citric acid may be associated with continued metabolic activity or transformation during storage [Agius et al. 2018, Paolo et al. 2019, Kıralan and Gündoğdu 2021, Kaygısız et al. 2025]. The variability observed among fertilization treatments further suggests that nutrient availability prior to harvest modulates the rate and extent of these transformations. In contrast to citric acid, malic, succinic, and fumaric acids showed substantial increases during the second period. These increases can be attributed to a combination of concentration effects resulting from water loss and ongoing metabolic conversions within organic acid pathways. Drying-induced reduction in moisture content may enhance the apparent concentration of these acids, while residual metabolic activity during storage may contribute to their accumulation [Osunde and Musa Makama 2007, Hussein et al. 2016, Qiu et al. 2018, Omorodion and Obiobu 2025]. The strong fertilization-dependent variation observed in these acids indicates that pre-harvest nutrient management influences both initial metabolite

levels and their subsequent evolution during storage. The observed variability in organic acids is consistent with previous reports indicating that cultivation practices, particularly organic and organomineral fertilization systems, significantly influence carbon allocation and organic acid metabolism in tomato fruits [Oliveira et al. 2013, Paolo et al. 2019, Fibiani et al. 2022]. These findings suggest that fertilization strategies modulate the metabolic framework of the fruit, thereby determining its biochemical response during post-drying storage. Antioxidant capacity was significantly affected by fertilization and post-drying period, while the interaction effect was not significant, indicating that these factors independently contributed to antioxidant behavior. The marked increase in antioxidant capacity during storage suggests enhanced extractability and stabilization of antioxidant compounds in the dried matrix. This response is likely associated with structural changes induced by drying, including cell wall disruption and reduced water activity, which limit enzymatic degradation and facilitate the release of bound antioxidants [Dewanto et al. 2002]. Consistent with this interpretation, previous studies have reported higher antioxidant activity in dried tomato products compared to fresh fruits [Chang et al. 2006, Ayan 2010]. Total phenolic content was highly sensitive to both fertilization and storage period, as well as their interaction, indicating a strong dependence on both pre- and post-harvest factors. The increase observed during storage suggests that phenolic compounds were either preserved or became more extractable over time. This may be explained by drying-induced disruption of cellular structures, which enhances the release of bound phenolics, combined with reduced oxidative degradation under low moisture conditions [Jorge et al. 2018]. The higher phenolic content observed in organic-based fertilization treatments further confirms that organic nutrient sources stimulate phenolic metabolism, likely through their effects on plant stress responses and carbon allocation. Overall, the results demonstrate that the biochemical evolution of dried tomatoes is governed by a complex interaction between fertilization strategy, drying-induced structural changes, and storage-related metabolic processes. These findings emphasize that fertilization practices not only determine the initial biochemical composition of tomato fruits, but also play a critical role in regulating their stability and transformation during post-drying storage.

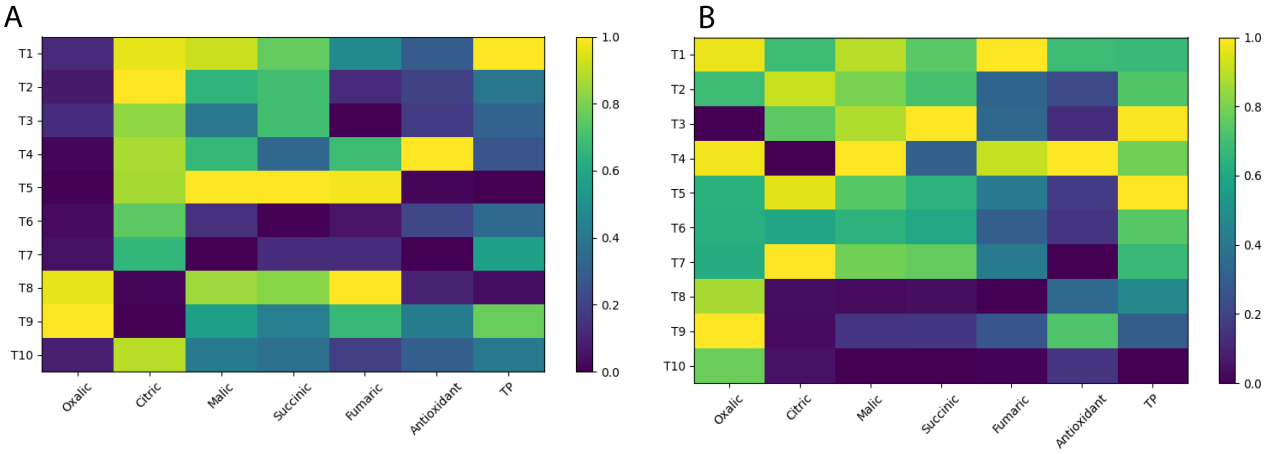
Figure 2. Interaction effects of fertilization regime and storage period on total phenolic content and antioxidant capacity of dried tomato samples



As illustrated in Figure 2, the direction and magnitude of changes in total phenolic content and antioxidant capacity during storage varied depending on the fertilization regime. These graphical trends support the statistical results presented in Tables 5 and 6, demonstrating that certain fertilization treatments were more effective in preserving or enhancing phenolic compounds and antioxidant capacity during the storage period. To evaluate these trends from a more integrative perspective, heatmap analyses constructed for P1 and P2 (Figure 3) revealed treatment-dependent variation patterns across biochemical parameters. In the P1 heatmap, organic acids exhibited noticeable variability among treatments, whereas total phenolic content and antioxidant capacity did not show a consistent association with these compounds. This observation suggests that the biochemical system had not yet reached equilibrium immediately after drying, and that time-dependent metabolic adjustments were still ongoing. Similar dynamic changes in phenolic and antioxidant components during post-processing, influenced by cultivation practices, have been reported previously [Toor and Savage 2006, Vallverdú-Queralt et al. 2011].

As storage progressed, the P2 heatmap showed more coordinated variation patterns among certain parameters, particularly total phenolic content, malic acid, and succinic acid. This indicates that prolonged storage promoted metabolic reorganization and strengthened the influence of fertilization strategies on the biochemical profile of dried tomatoes. Previous studies have also reported that during storage and processing, phenolic compounds may stabilize and antioxidant capacity may increase over time [Dewanto et al. 2002].

Figure 3. Heatmaps showing variation in organic acids, total phenolic content, and antioxidant capacity of dried tomatoes under different fertilization treatments in A) Period 1 and B) Period 2



The six-month post-harvest storage period generally resulted in increased levels of malic acid, fumaric acid, and succinic acid, as well as total phenolic content and antioxidant capacity in dried tomatoes. Previous studies have indicated that extended storage periods can influence the stability and transformation of biochemical compounds in tomato products [Bakir et al. 2023]. In contrast, reductions in polyphenol content and antioxidant activity have been reported during shorter storage durations (7–21–35 days), particularly under accelerated storage conditions involving elevated temperature and oxygen exposure [Nyawo et al. 2025]. Under the drying and storage conditions applied in the present study, reduced water activity, slowed enzymatic reactions, and concentration effects may have contributed to the relative stability of phenolic compounds and antioxidant capacity. In conclusion, the behavior of total phenolic content and antioxidant capacity in dried tomatoes during storage was shown to depend not only on storage duration, but also on pre-harvest conditions, particularly fertilization strategy, as well as the combined effects of drying and storage processes. Among fertilization treatments, T3 (vermicompost) was most effective in enhancing succinic acid and phenolic compounds, whereas T4 (organomineral fertilizer) was associated with higher malic acid content and antioxidant capacity. These findings demonstrate that soil nutrient management can modulate fruit biochemical composition in a multidimensional manner.

CONCLUSION

This study demonstrated that fertilization strategies play a decisive role in shaping the biochemical composition, and long-term stability of dried tomatoes. Total phenolic content, antioxidant capacity, and organic acid profiles were significantly influenced by fertilization treatments, drying period, and their interaction, indicating that both pre-harvest management and post-drying processes contribute to the final quality of the product. The results showed that immediately after drying (P1), organic acids responded sensitively to fertilization regimes. However, antioxidant activity and total phenolic content did not consistently align with organic acid patterns, suggesting that biochemical stabilization was not fully established at this stage. In contrast, after six months of storage (P2), a more coherent biochemical profile emerged, particularly among malic acid, succinic acid, and total phenolic content. Heatmap analyses further confirmed that prolonged storage promoted metabolic reorganization, and enhanced the expression of fertilization-dependent biochemical traits. These findings indicate that fertilization strategies not only affect the initial accumulation of bioactive compounds, but also influence their stability during long-term storage. The observed fertilization and period interaction highlights that the response

of biochemical parameters to storage is treatment-specific rather than uniform. Therefore, optimizing fertilization practices before harvest may be as critical as post-harvest handling in preserving the nutritional and functional quality of dried tomatoes. Overall, this study emphasizes that the biochemical stability of dried tomatoes is determined by an integrated effect of fertilization management and drying-related processes. The results provide valuable insights for producers and processors aiming to improve the quality, stability, and functional properties of dried tomato products through targeted fertilization strategies. Despite these findings, some limitations should be acknowledged. The study was conducted under specific environmental and storage conditions, and therefore the results may vary under different climatic conditions or storage environments. In addition, the evaluation was limited to selected biochemical parameters, and other quality attributes such as sensory properties and volatile compounds were not considered. Future research should focus on evaluating different drying techniques and storage conditions in combination with fertilization strategies, as well as incorporating sensory and metabolomic analyses to achieve a more comprehensive understanding of quality changes in dried tomatoes.

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CONFLICT OF INTEREST

The author declares that there is no conflict of interest.

DECLARATION OF THE USE OF GENERATIVE AI TOOLS

No generative AI tools were used in the preparation of this manuscript.

AUTHORS CONTRIBUTION

The author solely conceived and designed the study, conducted the experiments, performed the analyses, interpreted the data, and wrote and approved the final manuscript.

REFERENCES

Agius, C., Von Tucher, S., Poppenberger, B. et al. (2018). Quantification of sugars and organic acids in tomato fruits. MethodsX, 5, 537–550. https://doi.org/10.1016/j.mex.2018.05.014

Ayan, H. (2010). Güneşte ve yapay kurutucuda kurutulmuş domates (*Lycopersicum esculentum*) üretimi ve proses sırasındaki değişimlerin belirlenmesi [Sun dried and artificially dried tomato (*Lycopersicum esculentum*) production and changes during the process]. Master's thesis, Ankara University.

Bakir, S., Hall, R.D., de Vos, R.C., Mumm, R., Kadakal, Ç., Capanoglu, E. (2023). Effect of drying treatments on the global metabolome and health-related compounds in tomatoes. Food Chem., 403, 134123. https://doi.org/10.1016/j.foodchem.2022.134123

Bayana, D., İçier, F. (2024). Effects of process conditions on drying of tomato pomace in a novel daylight simulated photovoltaic-assisted drying system. Food Bioproc. Technol., 17(12), 5000–5022. https://doi.org/10.1007/s11947-024-03411-2

Belwal, T., Cravotto, C., Prieto, M.A., Venskutonis, P.R., Daglia, M., Devkota, H.P., Cravotto, G. (2022). Effects of different drying techniques on the quality and bioactive compounds of plant-based products. A critical review on current trends. Drying Technol., 40(8), 1539–1561. https://doi.org/10.1080/07373937.2022.2068028

Benzie, I.E.F., Strain, J.J. (1996).The ferric reducing ability of plasma (FRAP) as a measure of "antioxidant power": the FRAP assay. Anal. Biochem., 239(1), 70–76. https://doi.org/10.1006/abio.1996.0292

Bevilacqua, A.E., Califano, A.N. (1989). Determination of organic acids in dairy products by high performance liquid chromatography. J. Food Sci., 54(4), 1076. https://doi.org/10.1111/j.1365-2621.1989.tb07948.x

Chang, C.H., Lin, H.Y., Chang, C.Y., Liu, Y.C. (2006). Comparisons on the antioxidant properties of fresh, freeze-dried and hot-air-dried tomatoes. J. Food Eng., 77(3), 478–485. https://doi.org/10.1016/j.jfoodeng.2005.06.061

Dewanto, V., Wu, X., Adom, K.K., Liu, R.H. (2002). Thermal processing enhances the nutritional value of tomatoes by increasing total antioxidant activity. J. Agric. Food Chem., 50(10), 3010–3014. https://doi.org/10.1021/jf0115589

Fibiani, M., Paolo, D., Leteo, F., Campanelli, G., Picchi, V., Bianchi, G., Lo Scalzo, R. (2022). Influence of year, genotype and cultivation system on nutritional values and bioactive compounds in tomato (*Solanum lycopersicum* L.). Food Chem., 389. https://doi.org/10.1016/j.foodchem.2022.133090

Fterich, M., Elamy, M.I., Touti, E., Bentaher, H. (2023). Experimental and numerical study of tomatoes drying kinetics using solar dryer equipped with PVT air collector. Eng. Sci. Technol. Int. J., 47, 101524. https://doi.org/10.1016/j.jestch.2023.101524

González-Coria, J., Lozano-Castellón, J., Jaime-Rodríguez, C., Olmo-Cunillera, A., Laveriano-Santos, E.P., Pérez, M., Romanyà, J. (2022). The effects of differentiated organic fertilization on tomato production and phenolic content in traditional and high-yielding varieties. Antioxidants, 11(11), 2127. https://doi.org/10.3390/antiox11112127

Hussein, J.B., Sanusi, M.S., Filli, K.B. (2016). Evaluation of drying methods on the content of some bio-actives (lycopene, Î²-carotene and ascorbic acid) of tomato slices. Afr. J. Food Sci., 10(12), 359–367. https://doi.org/10.5897/AJFS2016.1470

Jorge, A., Sauer Leal, E., Sequinel, R., Sequinel, T., Kubaski, E.T., Tebcherani, S.M. (2018). Changes in the composition of tomato powder (*Lycopersicon esculentum* Mill) resulting from different drying methods. J. Food Proc. Preserv., 42(5), e13595. https://doi.org/10.1111/jfpp.13595

Jorge, M.F., Nascimento, K.D.O.D., Barbosa, J.L., Silva, L.D.B.D., Barbosa, M.I.M.J. (2017). Physicochemical characteristics, antioxidant capacity and phenolic compounds of tomatoes fertigated with different nitrogen rates. Rev. Caatinga, 30(1), 237–243. https://doi.org/10.1590/1983-21252017v30n126rc

Kaygısız, T., Sen, F., Gundogdu, M., Ejaz, S., Aglar, E. (2025). Effect of postharvest melatonin and salicylic acid applications on quality characteristics and primary and secondary metabolite physiology of tomato fruits. BMC Plant Biol., 25(1), 1090. https://doi.org/10.1186/s12870-025-07013-8

Kıralan, M., Gündoğdu, M. (2021). Dut türlerine ait meyvelerin organik asit ve C vitamini içerikleri üzerine farklı kurutma tekniklerinin etkisi [Effect of different drying techniques on organic acid and vitamin C contents of mulberry species fruits]. Uluslararası Tarım ve Yaban Hayatı Bilimleri Dergisi, 7(3), 404–411. https://doi.org/10.24180/ijaws.990049

Nyawo, O.K., Molelekoa, T.B.J., Da Silva, L.S., Beswa, D. (2025). Effect of drying methods on colour stability, lycopene retention, total phenolic content, total flavonoid content, and antioxidant activity of dried tomatoes under accelerated storage conditions. Int. J. Food Sci. Technol., 60(2), vvaf185. https://doi.org/10.1093/ijfood/vvaf185

Oliveira, A.B., Moura, C.F., Gomes-Filho, E., Marco, C.A., Urban, L., Miranda, M.R.A. (2013). The impact of organic farming on quality of tomatoes is associated to increased oxidative stress during fruit development. PLoS One, 8(2), e56354. https://doi.org/10.1371/journal.pone.0056354

Omorodion, N.J., Obiobu, E.R. (2025). Analysis of microbial and physio-chemical attributes in fresh, sun-dried, and oven-dried tomatoes (*Solanum lycopersicum* L.). Vokasi Unesa Bull. Eng. Technol. Appl. Sci., 2(1), 88–99. https://doi.org/10.26740/vubeta.v2i1.35906

Osunde, Z.D., Musa Makama, A.L. (2007). Assessment of changes in nutritional values of locally sun-dried vegetables. AU J. T., 10(4), 248–253.

Paolo, D., Bianchi, G., Morelli, C.F., Speranza, G., Campanelli, G., Kidmose, U., Lo Scalzo, R. (2019). Impact of drying techniques, seasonal variation and organic growing on flavor compounds profiles in two Italian tomato varieties. Food Chem., 298. https://doi.org/10.1016/j.foodchem.2019.125062

Perea-Domínguez, X.P., Hernández-Gastelum, L.Z., Olivas-Olguin, H.R., Espinosa-Alonso, L.G., Valdez-Morales, M., Medina-Godoy, S. (2018). Phenolic composition of tomato varieties and an industrial tomato by-product: free, conjugated and bound phenolics and antioxidant activity. J. Food Sci. Technol., 55(9), 3453–3461. https://doi.org/10.1007/s13197-018-3269-9

Qiu, J., Vuist, J.-E., Boom, R.M., Schutyser, M.A. (2018). Formation and degradation kinetics of organic acids during heating and drying of concentrated tomato juice. LWT – Food Sci. Technol., 87, 112–121. http://dx.doi.org/10.1016/j.lwt.2017.08.081

Swain, T., Hillis, W.E. (1959). The phenolic constituents of *Prunus domestica*. I. – The quantitative analysis of phenolic constituents. J. Sci. Food Agric., 10(1), 63–68. https://doi.org/10.1002/jsfa.2740100110

Toor, R.K., Savage, G.P. (2006). Effect of semi-drying on the antioxidant components of tomatoes. Food Chem., 94(1), 90–97. https://doi.org/10.1016/j.foodchem.2004.10.054

Vallverdú-Queralt, A., Arranz, S., Medina-Remón, A., Casals-Ribes, I., Lamuela-Raventós, R.M. (2011). Changes in phenolic content of tomato products during storage. J. Agric. Food Chem., 59(17), 9358–9365. https://doi.org/10.1021/jf202140j