

Article

Unraveling the Effects of Environment, Deficit Irrigation and Genotype on Yield, Sensory Quality and Antioxidants in Tomato: A Multivariate Analysis

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Abstract

Tomato is a high-value crop whose productivity and quality are threatened by climate change in semi-arid Mediterranean areas. This study examined the effects of environment, deficit irrigation (DI), and genotype on tomato yield as well as sensory and antioxidant characteristics. Field experiments were conducted over two consecutive seasons (2023–2024) at two sites in eastern Sicily differing in soil texture (clayey and sandy). Five genotypes—including two old local landraces of long shelf-life tomato and three hybrids—were subjected to three irrigation regimes based on the replenishment of crop evapotranspiration (ETc): 33% (I33, low irrigation rate), 66% (I66, moderate irrigation rate), and 99% (I99, high irrigation rate, control). Yield was maximized in clayey soil (+55% in 2023 and +44% in 2024) and under the I99 regime (48.48 Mg ha^{−1}). Among the genotypes, the most productive were the hybrids HL1 (‘Lycomech’, high-lycopene tomato) and MP (‘Febo’, mini-plum tomato), with yields exceeding 40 Mg ha^{−1}. Overall, old landraces showed lower productivity. Sensory quality (total solids—TS; total soluble solids—TSS; titratable acidity—TA; TSS/TA) and antioxidant quality (total phenols—TPs; flavonoids—Flavs; antioxidant activity—AA) were superior in sandy soil. Regarding irrigation, the highest overall quality was achieved with the I33 regime. The moderate irrigation regime in I66 limited the yield reduction compared to I33 and improved TSS, reducing sugars, TPs, Flavs, vitamin C, and AA compared to I99, although lycopene content decreased. Among the tomato cultivars examined, old local landraces, specifically the ‘Vulcano’ landrace, demonstrated greater stability and drought resilience than the three hybrids, maintaining their sensory and antioxidant quality across different environments and water regimes. Multivariate data analysis, using principal component analysis (PCA) and K-means clustering, was conducted to assess the impact of experimental factors on the studied traits and to identify groupings based on similarities. In conclusion, local landraces of long shelf-life tomato appear better adapted to conditions of low soil water availability than the new hybrids. DI restoring the 66% ETc offers a viable compromise between fruit quantity and quality for these old genotypes, potentially facilitating their reintroduction into sustainable, low-input cropping systems in Mediterranean regions. DI also represents a viable agronomic option for the new hybrids, enabling the maintenance of satisfactory yield and fruit quality levels while simultaneously saving significant amounts of irrigation water.



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Keywords: *Solanum lycopersicum*; new hybrids; old landraces; water regime; PCA; K-means

1. Introduction

Tomato (*Solanum lycopersicum* L.) is one of the most important vegetables worldwide, both in terms of economic value and nutritional benefits. Global tomato production reached approximately 186 million tons in 2022 [1], with China leading the world market, by contributing one-third of the total output, followed by India and Turkey [2]. In Europe, Italy is a major producer, with an annual production ranging between 5.5 and 6.5 million tons [3].

The recognized importance of the tomato is ascribed to its role as a major dietary source of vitamins (i.e., vitamins C and A), potassium, and lycopene, along with other antioxidants, which contribute significantly to human nutrition and health [4,5]. New, highly productive hybrids, such as those rich in lycopene (high-lycopene types), are unceasingly being released by seed companies [6,7]. These new tomatoes offer maximum yields when grown in a specific environment where they are well adapted. However, when moved to other environments or cultivated in different seasons, they may exhibit inconsistent performances, especially when growth conditions become unfavorable [8]. In this regard, in the scenario of climate change, more stable genotypes are recommended. Moreover, generally, newly released tomatoes are high-yielding when their water requirements are fulfilled, but may change their agronomic behavior under conditions of limited soil water availability [9]. Conversely, old local landraces (e.g., those of long shelf-life tomato) exhibit high resilience to drought and an important nutritional profile due to their long-term adaptation to semi-arid conditions; however, low yields limit their introduction into existing cropping systems [10].

Under climate change scenarios, increasing water scarcity and growing frequency and severity of drought pose significant challenges to tomato cultivation, especially in semi-arid Mediterranean areas such as those of Southern Italy [9]. In response to these challenges, deficit irrigation (DI) strategies emerged as an important water-saving approach, minimizing yield losses while maintaining or enhancing key fruit quality traits [11,12]. DI may be successfully applied to new tomato hybrids to save irrigation water, and to local landraces to promote plant productivity, keeping in mind that both tomato types (new hybrids and old landraces) represent a valuable genetic resource for the tomato.

Principal component analysis (PCA) is a multivariate statistical technique used to identify the primary sources of variability in a dataset. It reduces the dimensionality of the dataset when many variables are considered together, while preserving as much of its original variability as possible. In PCA, the original variables, in some cases highly intercorrelated, are grouped into new sets of variables (principal components) that are independent, with the first few accounting for most of the total variation [13]. PCA is mainly employed in genetic studies to assist breeders in evaluating genetic variability within a set of genotypes [14,15]; nevertheless, it can also offer valuable insights into the role of different traits in distinguishing agronomic treatments.

The 'K-means' algorithm is used for collecting data points (observations) based on their similarity into distinct groups (clusters) by minimizing the sum of the squares of the distances from their centroid (mean value of the cluster) [16]. Points with maximum similarity are considered members of the same cluster.

The integration of PCA and K-means clustering represents a robust approach for exploiting genetic variability within tomato germplasm to identify genotypes that are more drought-tolerant and better adapted to changing environments [15].

This study aimed to evaluate the effects of deficit irrigation regimes on fruit yield and quality, including both sensory and antioxidant traits, in a set of tomatoes, including old local landraces of long shelf-life tomato and new hybrids. Field experiments were conducted over two consecutive seasons (2023 and 2024) at two sites in Eastern Sicily differing in soil texture, thereby representing distinct agro-environmental conditions. A combined

multivariate approach, including principal component analysis (PCA) and K-means clustering, was applied to identify the agronomic traits that best discriminate among treatments and assess the variability in agronomic performance across the different cropping systems. The ultimate goal of the study was to identify tomato genotypes exhibiting either specific adaptation to individual environments or stable performance across multiple environments, thereby supporting crop selection strategies in the face of changing climate scenarios.

2. Materials and Methods

2.1. Open-Field Experiment

A two year-experiment (2023–2024) was conducted in open fields in two environments (sites) of the eastern coast of Sicily (South Italy), differing mainly in soil texture: the first mostly clayey (Site1, 10 m a.s.l., 37°24′35.8″ N Lat, 15°03′31.7″ E Long), the second mostly sandy (Site2, 12 m a.s.l., 37°28′37.6″ N Lat, 15°03′57.6″ E Long) (Table 1).

Table 1. Soil physic-chemical characteristics of the two sites of field experiment.

Soil Characteristics	Unit	Value	
		Site1	Site2
Sand	%	34.1	55.9
Loam	%	26.5	19.8
Clay	%	39.4	24.3
Organic matter	%	2.4	1.5
pH	-	8.6	8.6
Total N	‰	3.2	2.3
Available P ₂ O ₅	ppm	39	31
Exchangeable K ₂ O	ppm	915	585
Bulk density	g cm ⁻³	1.1	1.4
Field capacity (−0.03 MPa)	%	27.0	23.5
Wilting point (−1.5 MPa)	%	11.0	10.0

Five tomato genotypes, among them old, traditional, and new tomato types, were assessed (Table 2). The two old local Sicilian landraces of long shelf-life tomato belong to the germplasm collection at CNR-IBE (Catania, Italy).

Table 2. List of tomato genotypes assessed in the field experiment.

Tomato Name	Type	Code	Provenance/Seed Company
Vulcano	Long shelf-life (old)	LS1	Vulcano, Aeolian Island (Italy)
Pizzutello	Long shelf-life (old)	LS2	Sciacca, Agrigento (Italy)
Febo Hy.	Mini-plum (traditional)	MP	Syngenta Seeds (Milan, Italy)
Lycomech Hy.	High lycopene (new)	HL1	United Genetics Italia, Parma (Italy)
Lycostar Hy.	High lycopene (new)	HL2	United Genetics Italia, Parma (Italy)

In both environments, all tomatoes were cultivated under three irrigation regimes: I33 (low irrigation rate), I66 (moderate irrigation rate), and I99 (high irrigation rate, control). These regimes restored 33, 66, and 99% of crop evapotranspiration (ET_c) over the growing season, respectively. At each site, treatments were arranged in a 3 × 5 split-plot design with three replicates. Irrigation was assigned to the main plot and genotype to the subplot. Irrigation regimes were randomly distributed within each replicate (block), and genotypes were randomly distributed within each irrigation regime (plot). Each plot measured 10.8 m² (3.0 × 3.6 m). Plants were spaced 0.75 m between rows and 0.40 m within rows, yielding a final plant density of 3.3 plants m⁻².

Transplant in the open field occurred when plants were at the 4-leaf stage, on 20 April 2023, and 23 April 2024, at Site1, and on 19 April 2023, and 22 April 2024, at Site2. Before plant transplant, 75, 100, and 100 kg ha⁻¹ of N (as ammonium sulphate), P₂O₅ (as mineral perphosphate), and K₂O (as potassium sulphate), respectively, were applied. Thirty days after transplanting, a further 75 kg ha⁻¹ of N (as ammonium nitrate) was supplied as top dressing. Irrigation water was distributed through a polyethylene (PE) drip tape with an outer diameter of 16 cm and pressure-compensating emitters spaced 40 cm apart (emitter flow rate: 2.1 L h⁻¹). At transplant, an equal amount of water was distributed to all plots (40–45 mm in 2023 and 50–55 mm in 2024) to restore field capacity, considering soil water content measured on five soil samples randomly collected at a 0.4 m soil depth and oven-dried at 105 °C. Thereafter, irrigation regimes were differentiated, restoring 33, 66, and 99% ET_c in I33, I66, and I99, respectively. The ET_c to restore at each irrigation was calculated as $ET_0 \times k_p \times k_c$, where ET₀ is the reference ET measured in a class-A evaporation pan, k_p is the pan coefficient, equal to 0.80 in a semi-arid environment [17], and k_c are the following crop coefficients reported for tomato [12]: 0.4–0.7 from transplanting to crop establishment; 0.7–1.1 from crop establishment to beginning of flowering; 1.1–0.8 from beginning of flowering to beginning of fruit set; and 0.8–0.6 from beginning of fruit set to full maturity of the first and second truss fruits. The amount of water to supply with irrigation (V) was that required to fill the soil up to field capacity in the 0–40 cm soil depth, where most of the roots are expected to grow, calculated based on maximum available soil water content in the first 0.4 m of soil depth [12]. According to Doorenbos and Pruitt [17], 66% of available soil water content (ASWC: soil water content between field capacity and wilting point) is generally assumed as the irrigation threshold, representing the fraction of readily available soil water that allows unrestricted evapotranspiration. Irrigation was applied when cumulative ET_c corresponded to V (~51 mm and 46 mm, at Site1 and Site2, respectively); then the 33, 66, and 99% of V were calculated and distributed to I33, I66, and I99, respectively. Plots were irrigated approximately once or twice a week, depending on ET₀. All plots were irrigated until fruit ripening (early July). The total seasonal volume of water distributed at each site is reported in Table 3. The water was delivered by a public authority, collected into an artificial basin, and then distributed within the experimental farm. In both sites, the irrigation water had a salinity (electrical conductivity) < 2.0 dS m⁻¹.

Table 3. Seasonal amount of water (mm) distributed in each irrigation regime at the two experimental sites (in brackets, in %, the amount of water saved with respect to I99).

Irrigation Regime	Year 2023		Year 2024	
	Site1	Site2	Site1	Site2
I33	162 (54)	151 (53)	197 (57)	180 (56)
I66	258 (27)	233 (27)	325 (28)	295 (28)
I99	353	319	454	410

During the open-field experiments, meteorological variables (air minimum and maximum temperature, rainfall, and class A-pan evaporation) were recorded at both sites using data loggers (CR10, Campbell Scientific, Logan, UT, USA) placed 50 m apart.

The meteorological course recorded at the two experimental sites during the two growing seasons is reported in Figure 1. Year 2024 was slightly warmer than 2023, with maximum temperatures peaking two (Site2) to three (Site1) degrees higher. Between the two sites, Site1 was slightly cooler, with maximum temperatures peaking at 34 and 37 °C at Site1, and at 35 and 38 °C at Site2, in 2023 and 2024, respectively. In 2024, higher ET₀ at Site1

from mid-May onwards accounted for wider differences than in 2023 between the two sites in the total seasonal volume of water distributed to the crop. The mid- to late spring course was quite rainy in 2023 and dry in 2024, and the nearly 1 mm higher ET_0 in 2024, from transplant to harvest, explained the higher seasonal volume of irrigation water (+29% at both sites in I99) distributed to the crop in 2024.

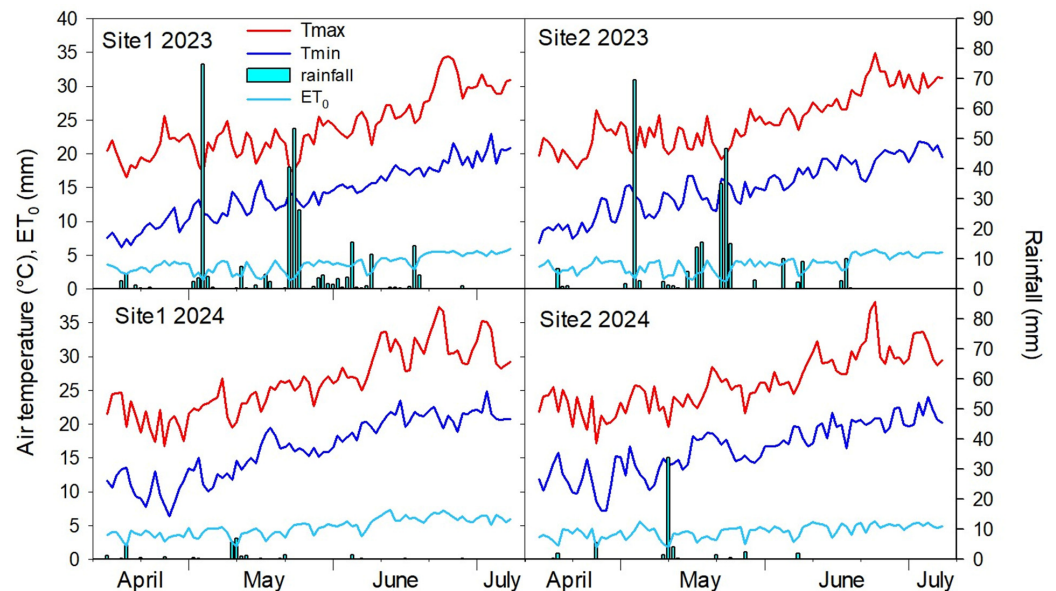


Figure 1. Meteorological course (minimum—Tmin—and maximum—Tmax—air temperature, rainfall, reference evapotranspiration— ET_0) recorded at the two experimental sites in the two growing seasons.

In the second year (2024), soil water deficit was assessed during field experiments in each irrigation regime, from early May until early July. To this end, soil water content was measured at both sites through gypsum blocks (Soilmoisture Equipment Corp., Santa Barbara, CA, USA) located at 0.4 m soil depth in all plots. Soil water content was measured immediately before and after each irrigation event at intervals of 4–5 days. From the values of soil water content, soil water deficit (SWD) was calculated as follows:

$$SWD (\%) = (1 - (WC - WP)/(FC - WP)) \times 100 \quad (1)$$

where WC is soil water content measured by gypsum block (as a percentage of dry soil); FC is soil water content at field capacity (as a percentage of dry soil); and WP is soil water content at wilting point (as a percentage of dry soil).

Fruits were harvested at full ripening (early to mid-July), and fruit yield was then calculated ($Mg\ ha^{-1}$ fresh weight—FW).

2.2. Laboratory Analyses

Laboratory analyses were conducted on fruits sampled at full ripening (~2 kg of fruits per treatment per replicate) for sensory and antioxidant quality measurements. These last were conducted in triplicate. Before analyses, fruits were washed to remove dirt, then dried with absorbent paper and homogenized in an Ultraturrax T25 (Janke & Kunkel, Staufen, Germany). All chemicals were provided by Sigma (Sigma-Aldrich s.r.l., Milan, Italy).

2.2.1. Sensory Quality Measurements

Sensory quality traits (total solids, total soluble solids, titratable acidity, reducing sugars) were measured in the laboratory.

Total solids (TS) were measured in homogenate samples (~20 g) dried at 65 °C in a thermo-ventilated oven until constant weight (72 h). TS were expressed as g 100 g⁻¹ FW.

Total soluble solids (TSS), expressed as °Brix, were measured in a portable digital refractometer (Hanna Instruments Digital Brix Refractometer, HI96801) at 20 °C. TSS were expressed as °Brix.

Titrateable acidity (TA) was determined by titration [18], using 0.1 M NaOH and phenolphthalein, the latter as an indicator. TA was expressed as g citric acid 100 g⁻¹ FW.

Reducing sugars (RSs) were measured spectrophotometrically (UV-30 Scan Spectrophotometer, Onda, Carpi, Italy) according to the 3,5-dinitrosalicylic acid (DNS) method proposed by Bailey et al. [19]. A 5 g homogenate sample was diluted in 5 mL distilled water, then centrifuged at 3500 × g for 5', and an aliquot was mixed with 1 mL of DNS reagent, then incubated in a water bath at 90 °C for 15'. The extracts were cooled in a cold water bath, then mixed with 1 mL of 40% sodium and potassium tartrate solution. Absorbance was read at 575 nm, using glucose (0 to 1 mg mL⁻¹) as a standard curve ($R^2 = 0.99$). RSs were expressed as g 100 g⁻¹ FW.

Finally, the TSS/TA ratio (SAR) was calculated [20].

2.2.2. Antioxidant Quality Measurements

Besides sensory quality traits, some antioxidants (ascorbic acid, total phenols, flavonoids, lycopene) and the antioxidant activity were also measured in all tomato samples.

Ascorbic acid (AscA) was estimated by titration, using a 2,6-dichlorophenolindophenol solution [18]. A 10 g sample of tomato homogenate was diluted in 5 mL of a 3% (w/v) metaphosphoric acid solution and 5 mL of an 8% (v/v) acetic acid solution, filtered, and titrated. Before the AscA measurement in tomato samples, the 2,6-dichlorophenolindophenol solution was standardized in a standard stock solution (1 mg mL⁻¹) of ascorbic acid with a known concentration. AscA was expressed as mg ascorbic acid 100 g⁻¹ FW.

Total phenols (TPs) were assayed spectrophotometrically according to Singleton et al. [21]. A 2 g sample of tomato homogenate was extracted in 10 mL of MeOH (80%). After 15 h incubation at room temperature and 5' centrifugation at 5000 × g, 125 µL of supernatant were diluted in 500 µL of distilled water, then mixed with 125 µL of the Folin-Ciocalteu reagent and, after a few minutes, with 1.5 mL of a 7% (w/v) Na₂CO₃ solution and 1 mL of distilled water. After 90' incubation in the dark at room temperature, the absorbance was read at 760 nm, using a curve of gallic acid (0 to 250 µg mL⁻¹) as standard ($R^2 = 0.99$). TPs were expressed as mg gallic acid equivalent (GAE) 100 g⁻¹ FW.

Flavonoids (Flavs) were assayed spectrophotometrically according to Ilahy et al. [22] with modification. A 2 g sample of tomato homogenate was extracted in 10 mL of MeOH (80%). The extract was incubated for 15 h at room temperature, then centrifuged for 5' at 5000 × g. After that, 50 µL of supernatant were diluted in 450 µL of distilled water; then 30 µL of 5% (w/v) Na₂CO₃ were added. After incubation for 6' at room temperature, 60 µL of 10% (w/v) AlCl₃ were added. Samples were incubated again for 5'; then 200 µL of 1 M NaOH and 210 µL of H₂O were added, and the mixture was vortexed. Absorbance was read at 510 using a curve of rutin (0 to 250 µg mL⁻¹) as a standard ($R^2 = 0.99$). Flavs were expressed as mg rutin equivalent (RE) 100 g⁻¹ FW.

Lycopene (Lyco) was estimated spectrophotometrically according to Anton and Barrett [23]. A 0.1 g sample of tomato homogenate was extracted in 8 mL of hexane/ethanol/acetone (HEA) mixture (2:1:1, v/v/v). The extract was incubated for 20' at room temperature in the dark, and 1 mL distilled H₂O was added. After that, the extract was incubated again at room temperature for 10' in the dark. Absorbance was read at 503 and 444 nm. Lyco content, expressed as mg 100 g⁻¹ FW, was calculated as:

$$\text{Lyco (mg 100 g}^{-1}\text{ FW)} = [(6.95 \times A_{503} - 1.59 \times A_{444}) \times 0.55 \times 537 \times V/W]/10 \quad (2)$$

where V (mL) is the volume of the added HEA mixture (8 mL) and W (g) is the weight of the homogenate tomato sample.

Antioxidant activity (AA, scavenging activity) was estimated spectrophotometrically using a 2,2-Diphenyl-1-picrylhydrazyl (DPPH) free radical-scavenging assay, according to Barbagallo et al. [24] with modification. A 2 g sample of tomato homogenate was mixed with 2 mL of a MeOH (80%) solution and incubated for 3' at 4 °C. Samples were centrifuged at 3500 × g for 5'; then 50 µL of supernatant were mixed with 1 mL of 0.1 M DPPH and incubated for 30' at room temperature in the dark. Absorbance was read at 517 nm, using DPPH without tomato extract as a blank. AA, expressed as %, was calculated as:

$$AA (\%) = \left[1 - \left(\frac{A_{517\text{sample}}}{A_{517\text{blank}}} \right) \right] \times 100 \quad (3)$$

where $A_{517\text{sample}}$ and $A_{517\text{blank}}$ are the absorbances, respectively of the tomato sample and blank, read at 517 nm.

2.3. Data Analysis

Each combination '*site* × *year*' was considered as an environment, for a total of four environments (Table 4). Data of fruit yield, sensory traits, and antioxidant quality were statistically analyzed using a three-way ANOVA within a mixed-effects model appropriate for split-plot design. *Irrigation* was assigned to main plots, while *genotype* was assigned to subplots. *Irrigation* and *genotype* were treated as fixed factors, whereas *environment* was considered as a random factor. The interactions among *environment* (E), *irrigation* (I), and *genotype* (G) were included in the model. Separate main-plot and subplot error terms were used. The statistical analysis was performed using Minitab Statistical Software version 19 (Minitab LLC, State College, PA, USA). Before ANOVA, the normality of residuals was checked by means of the Shapiro–Wilk test, and the homoscedasticity was tested by means of Bartlett's test. The independence of data was assumed through random sampling. Means were separated by Tukey's test at a 95% confidence level.

Table 4. List of the experimental environments.

Environment	Site	Year	Type of Soil	Avg Max T (°C)	Cumulative ET ₀ (mm)	Total Rainfall (mm)
E1	Site1	2023	clayey	24.0	355	268
E2	Site2	2023	sandy	24.9	354	234
E3	Site1	2024	clayey	26.3	423	28
E4	Site2	2024	sandy	26.2	396	54

A Pearson's pairwise correlation test was conducted to explore the relationships among yield, sensory, and nutritional traits (Minitab Statistical Software version 19, LLC).

A multivariate data analysis was performed using a principal component analysis (PCA) to reduce the complexity of the dataset and identify the primary sources of variation (Minitab Statistical Software version 19, LLC) [13]. To simplify the analysis, three distinct PCAs were conducted, considering (i) '*E* × *G*' (across irrigation levels); (ii) '*I* × *G*' (across environments); and (iii) '*E* × *I*' (across genotypes). Since the variables had different units and scales, they were standardized in PCA using the option 'correlation matrix' in Minitab. A biplot was made for each PCA, using a loading plot and a score plot for the first two components.

Finally, a ‘K-means’ clustering was applied to group all combinations of treatments for similarity into distinct clusters.

3. Results

3.1. Soil Water Deficit

The course of soil water deficit (SWD, %) measured in 2024 during the crop growing season at the two experimental sites is reported in Figure 2. SWD fluctuated according to the time of irrigation. At both sites, soil water content in I33 frequently dropped below the theoretical threshold for irrigation (SWD 66%); during the latter part of the season (from early June onwards), SWD rose to 100% just a few days after each irrigation. In fact, irrigation at a low rate (33% ET_c) failed to restore soil water content above 50% of field capacity (FC), and over the course of the growing season, all available water stored in the soil was lost to evapotranspiration and plant water uptake. SWD in I66 followed a pattern similar to that of I33, reaching 90% a few days after irrigation, and approaching 30% (Site1) or 20% (Site2) immediately after water application. Even with high irrigation volumes (I99 treatment), SWD dropped below the threshold; this was more pronounced at Site2, where the value often approached 90%, particularly from mid-June onwards. These results could be ascribed to the sandy texture of the soil at Site2, which likely caused water losses through percolation. Nevertheless, the high irrigation volumes of the I99 treatment were able to refill the soil to FC after each irrigation event.

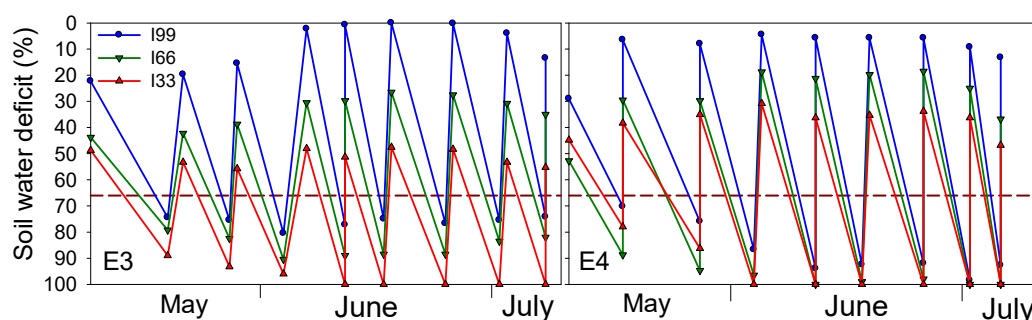


Figure 2. Soil water deficit at a depth of 0.40 m measured in each irrigation regime at the two environments (E3: Site1, 2024; E4: Site2, 2024). Constant horizontal short dash line indicates minimum threshold of available soil water content (year: 2024).

3.2. Fruit Yield

Fresh fruit yield was measured across the four environments. The higher seasonal irrigation volume applied to the crop in the second year (in environments E3 and E4), driven by higher ET₀, resulted in significantly higher yields than in environments E1 and E2. Higher productivity levels were achieved in the environments characterized by clayey soil (+44% in E3 with respect to E4, + 55% in E1 with respect to E2) (Table 5). As expected, fruit yield was maximized in I99 (48.48 Mg ha⁻¹), and declined progressively as the irrigation volume was reduced (down to 28.21 Mg ha⁻¹ in I33). Across all environments and irrigation regimes, the most productive genotypes were HL1 (‘Lycomech’, high-lycopene tomato) and MP (‘Febo’, mini-plum), both yielding over 40 Mg ha⁻¹. Overall, the old long shelf-life tomatoes were less productive (~33 Mg ha⁻¹ for both landraces) than the new hybrids. However, among the experimental factors, ‘genotype’ contributed the least to the total variance (6.5%) (Table 6).

Table 5. Fresh fruit yield (FY) in tomato in relation to *environment (E)*, *irrigation (I)*, and *genotype (G)* (ANOVA). For the main effects, values (mean $\pm$ SE) followed by the same letter are not significantly different at $p \leq 0.05$ (Tukey’s test). Genotype and environment codes are those reported in Tables 2 and 4, respectively.

Main Effect		Fruit Yield (Mg ha ^{−1})
Environment (E)	E1	37.65 $\pm$ 2.24 b
	E2	26.01 $\pm$ 1.33 d
	E3	55.27 $\pm$ 1.92 a
	E4	35.65 $\pm$ 1.04 c
Irrigation (I)	I33	28.21 $\pm$ 1.33 c
	I66	39.24 $\pm$ 1.74 b
	I99 (control)	48.48 $\pm$ 1.96 a
Genotype (G)	LS1	33.36 $\pm$ 1.73 c
	LS2	33.11 $\pm$ 2.38 c
	MP	42.45 $\pm$ 2.68 a
	HL1	43.91 $\pm$ 2.89 a
	HL2	40.39 $\pm$ 2.65 b
Significance	E	***
	I	***
	G	***
	E $\times$ I	***
	E $\times$ G	***
	I $\times$ G	***
	E $\times$ I $\times$ G	***

Significant at $p \leq 0.001$ (***).

Table 6. Results of ANOVA for fruit yield and quality traits in tomato. FY: fruit yield; TS: total solids; TSS: total soluble solids; TA: titratable acidity; RSs: reducing sugars; SAR: total soluble solids to titratable acidity ratio; AscA: ascorbic acid; TPs: total phenols; Flavs: flavonoids; Lyco: lycopene; AA: antioxidant activity. *df*: degrees of freedom; Adj MS: adjusted mean square.

Source	<i>df</i>	FY	TS	TSS	TA	RSs	SAR	AscA	TPs	Flavs	Lyco	AA
Adj MS												
E	3	6686.7	23.00	13.32	0.007	3.50	64.9	4313.4	895.7	2457.9	71.3	193.8
I	2	6182.1	9.33	7.55	0.007	0.46	23.5	15.8	835.7	555.7	42.7	382.9
G	4	934.2	70.02	22.29	0.071	5.68	458.3	381.0	952.1	835.9	1131.3	279.5
E $\times$ I	6	300.1	1.29	0.20	0.001	0.09	6.3	7.0	98.4	27.3	15.6	20.7
E $\times$ G	12	145.8	0.88	0.66	0.004	0.51	34.7	100.3	176.1	95.3	56.2	53.0
I $\times$ G	8	110.3	1.19	0.61	0.002	0.17	27.9	8.6	18.2	85.5	7.5	17.9
E $\times$ I $\times$ G	24	63.1	0.66	0.33	0.002	0.11	43.2	13.3	17.7	17.2	8.6	7.0
Error	120	7.3	0.25	0.10	0.001	0.02	7.1	3.2	19.6	5.7	1.4	6.2

A significant ‘E $\times$ I $\times$ G’ interaction in fruit yield revealed different responses of genotypes to the irrigation regime, depending on the environment (Figure 3). Overall, in E1, E2, and E3, the promoting effect of irrigation (shifting from I33 to I99) on yield was quite pronounced for all genotypes. In contrast, in E4 (sandy soil, year 2024), this effect was clearly evident only for MP (‘Febo’).

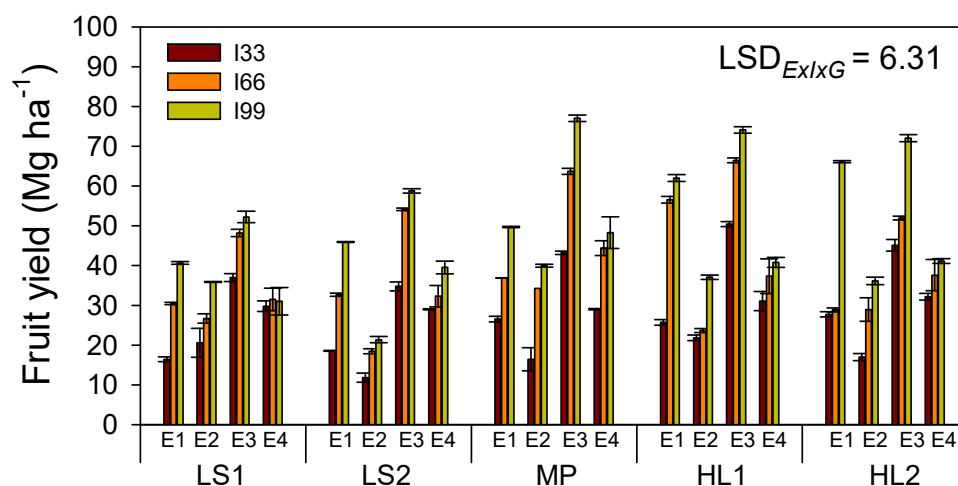


Figure 3. Effect of interaction ‘environment $\times$ irrigation $\times$ genotype’ ($E \times I \times G$) on fruit yield (Mg ha^{-1}) in tomato (I33, I66, I99: 33, 66, 99% ETc restoration, respectively). Genotype and environment codes are those reported in Tables 2 and 4, respectively. Standard errors are also indicated ($n = 3$).

3.3. Sensory Traits

TS and TSS varied significantly, depending on the environment, irrigation regime, genotype, and their interactions. Among these factors, ‘genotype’ contributed the most to the total variance (66 and 50%, for TS and TSS, respectively), whereas the contribution of ‘irrigation’ was lower (8.8 and 16.6%). Significantly higher TS and TSS were observed in tomato fruits grown in E4 (sandy soil, year 2024) (Table 7).

Table 7. Quality traits in tomato in relation to environment (E), irrigation (I), and genotype (G) (ANOVA). TS: total solids; TSS: total soluble solids; TA: titratable acidity; RSs: reducing sugars; SAR: total soluble solids to titratable acidity ratio. For the main effects, values (mean $\pm$ SE) followed by the same letter are not significantly different at $p \leq 0.05$ (Tukey’s test). Genotype and environment codes are those reported in Tables 2 and 4, respectively.

Main Effect		TS ($\text{g } 100 \text{ g}^{-1}$)	TSS ($^{\circ}\text{Brix}$)	TA ($\text{g } 100 \text{ g}^{-1}$)	RSs ($\text{g } 100 \text{ g}^{-1}$)	SAR
Environment (E)	E1	$8.66 \pm 0.22 \text{ c}$	$6.80 \pm 0.14 \text{ c}$	$0.25 \pm 0.007 \text{ b}$	$2.49 \pm 0.073 \text{ a}$	$27.61 \pm 0.66 \text{ a}$
	E2	$9.51 \pm 0.25 \text{ b}$	$7.30 \pm 0.13 \text{ b}$	$0.26 \pm 0.005 \text{ b}$	$2.42 \pm 0.071 \text{ b}$	$27.91 \pm 0.52 \text{ a}$
	E3	$8.75 \pm 0.20 \text{ c}$	$6.31 \pm 0.14 \text{ d}$	$0.26 \pm 0.010 \text{ b}$	$1.87 \pm 0.077 \text{ d}$	$25.32 \pm 0.91 \text{ b}$
	E4	$10.18 \pm 0.20 \text{ a}$	$7.53 \pm 0.12 \text{ a}$	$0.28 \pm 0.009 \text{ a}$	$2.21 \pm 0.045 \text{ c}$	$27.58 \pm 0.85 \text{ a}$
Irrigation (I)	I33	$9.72 \pm 0.22 \text{ a}$	$7.37 \pm 0.12 \text{ a}$	$0.28 \pm 0.008 \text{ a}$	$2.34 \pm 0.063 \text{ a}$	$27.46 \pm 0.70 \text{ a}$
	I66	$9.12 \pm 0.19 \text{ b}$	$6.93 \pm 0.12 \text{ b}$	$0.26 \pm 0.006 \text{ b}$	$2.25 \pm 0.071 \text{ b}$	$27.48 \pm 0.73 \text{ a}$
	I99 (control)	$8.97 \pm 0.18 \text{ b}$	$6.66 \pm 0.13 \text{ c}$	$0.26 \pm 0.006 \text{ b}$	$2.16 \pm 0.063 \text{ c}$	$26.39 \pm 0.52 \text{ b}$
Genotype (G)	LS1	$10.19 \pm 0.12 \text{ b}$	$7.43 \pm 0.09 \text{ b}$	$0.25 \pm 0.005 \text{ b}$	$2.59 \pm 0.062 \text{ b}$	$30.37 \pm 0.78 \text{ a}$
	LS2	$11.27 \pm 0.20 \text{ a}$	$8.15 \pm 0.11 \text{ a}$	$0.31 \pm 0.007 \text{ a}$	$2.73 \pm 0.052 \text{ a}$	$26.69 \pm 0.51 \text{ b}$
	MP	$8.61 \pm 0.15 \text{ c}$	$6.63 \pm 0.11 \text{ c}$	$0.31 \pm 0.007 \text{ a}$	$2.01 \pm 0.031 \text{ d}$	$21.51 \pm 0.52 \text{ c}$
	HL1	$8.17 \pm 0.17 \text{ d}$	$6.38 \pm 0.15 \text{ d}$	$0.24 \pm 0.005 \text{ b}$	$1.78 \pm 0.053 \text{ e}$	$26.90 \pm 0.56 \text{ b}$
	HL2	$8.13 \pm 0.14 \text{ d}$	$6.33 \pm 0.14 \text{ d}$	$0.21 \pm 0.005 \text{ c}$	$2.15 \pm 0.093 \text{ c}$	$30.07 \pm 0.89 \text{ a}$
Significance	E	***	***	***	***	***
	I	***	***	***	***	*
	G	***	***	***	***	***
	$E \times I$	***	ns	ns	***	ns
	$E \times G$	***	***	***	***	***
	$I \times G$	***	***	***	***	***
	$E \times I \times G$	***	***	***	***	***

Significant at $p \leq 0.05$ (*) and 0.001 (***), ns: not significant.

Differences in TS and TSS between the two sites were more pronounced in the second season (TS 10.18 g 100 g⁻¹ and TSS 7.53 °Brix, at site E4, with sandy soil, i.e., 16 and 19% higher, respectively, than those measured at site E3, with clayey soil). Regarding the irrigation regime, the highest TS (9.72 g 100 g⁻¹) and TSS (7.37 °Brix) were measured in fruits produced under a low irrigation rate in I33. Among the cultivars, the best TS and TSS were observed in LS2 ('Pizzutello' of long shelf-life tomato). Both new hybrids (HL1 and HL2) exhibited significantly lower TS (<8.2 g 100 g⁻¹) and TSS (<6.4 °Brix).

The significant ' $E \times I \times G$ ' interaction ($p < 0.001$), observed for both TS and TSS, highlighted an irrigation effect that varied depending on the environment and genotype. For instance, for some cultivars (e.g., LS2 and MP), fruit TS content increased significantly in environments E2 and E4 (both with sandy soil), but not in E1 and E3 (both with clayey soil), when shifting from the 99 to the 33% irrigation level (Figure 4). Other cultivars (e.g., HL2) maintained TSS levels in I66 comparable to those in I33, across all environments, except for environment E3, where increasing the irrigation supply from 33 to 66% ETc resulted in a significant reduction in TSS content.

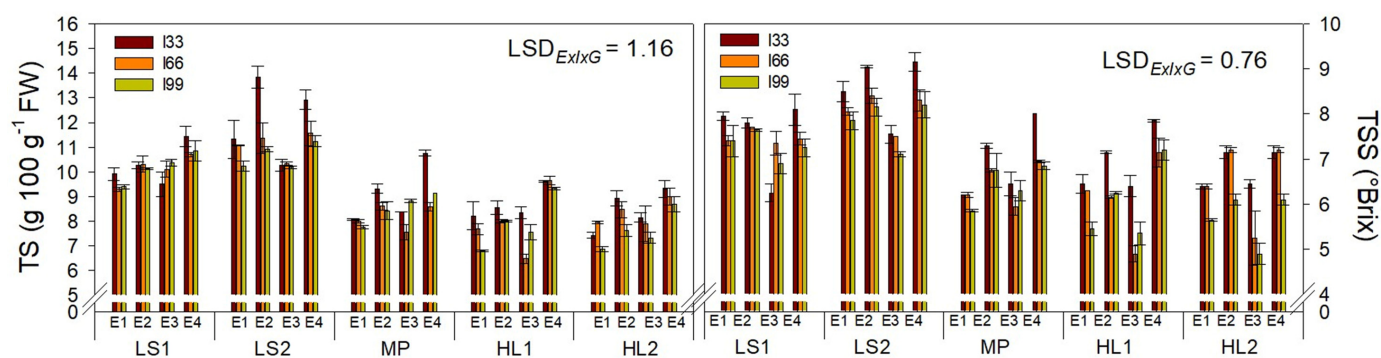


Figure 4. Effect of interaction ' $environment \times irrigation \times genotype$ ' ($E \times I \times G$) on the content of total solids (TS, on the left) and total soluble solids (TSS, on the right) in tomato (I33, I66, I99: 33, 66, 99% ETc restoration, respectively). Genotype and environment codes are those reported in Tables 2 and 4, respectively. Standard errors are also indicated ($n = 3$).

Fruits with significantly higher TA were obtained in E4 (E , $p < 0.001$). A low irrigation level in I33 increased fruit acidity (I , $p < 0.001$), driven by a higher concentration of organic acids, including citric acid. Among the genotypes, high-lycopene tomatoes exhibited lower overall TA (≤ 0.24 g citric a. 100 g⁻¹), whereas genotypes MP and LS2 had the highest fruit acidity (0.31 g 100 g⁻¹ for both). The significant ' $E \times I \times G$ ' interaction revealed a combined effect of all experimental factors on TA. For instance, fruit TA for genotypes HL1 and HL2 did not change according to irrigation regime across the different environments, or the irrigation effect was minimal, whereas fruits from genotypes LS1 and LS2 had significantly higher TA under low irrigation rate (in I33), in environment E3 (Figure 5).

Regardless of genotype and water regime, RSs were higher in fruits produced in E1 and E2 (both in the first season experiment) (E , $p < 0.001$). RSs were maximized in I33 (2.34 g 100 g⁻¹) and declined progressively as the volume of water applied by irrigation increased. The higher RSs observed in the fruits of both local landraces of long shelf-life tomato (LS1 and LS2, RSs ≥ 2.60 g 100 g⁻¹) indicated superior sensory quality in terms of sweetness. However, the genotypes exhibited different behaviors depending on the environment and water regime (' $E \times I \times G$ ', $p < 0.001$). For instance, in the first season, the RS content in the I66 treatment matched that of I33 for the two new HL hybrids grown on sandy soil (E2); conversely, for LS1 and MP, the content in I33 was higher than in I66, in the same environment (Figure 6).

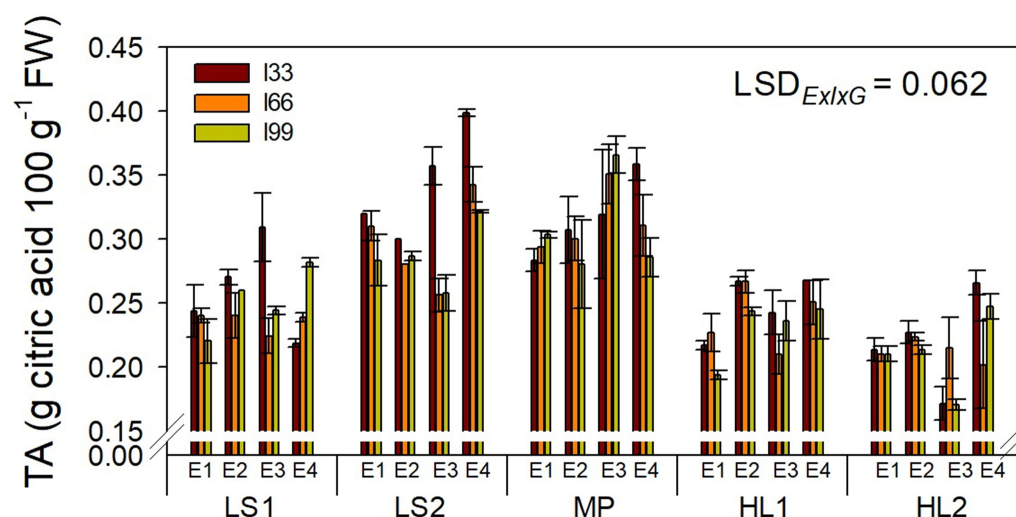


Figure 5. Effect of interaction ‘environment $\times$ irrigation $\times$ genotype’ ($E \times I \times G$) on the titratable acid content (TA) in tomato (I33, I66, I99: 33, 66, 99% ETc restoration, respectively). Genotype and environment codes are those reported in Tables 2 and 4, respectively. Standard errors are also indicated ($n = 3$).

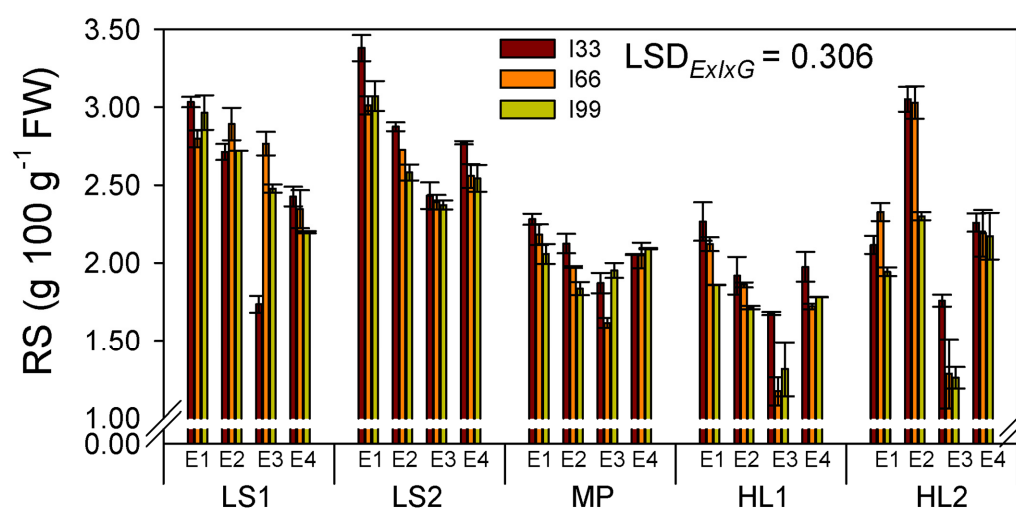


Figure 6. Effect of interaction ‘environment $\times$ irrigation $\times$ genotype’ ($E \times I \times G$) on the reducing sugar (RS) content in tomato (I33, I66, I99: 33, 66, 99% ETc restoration, respectively). Genotype and environment codes are those reported in Tables 2 and 4, respectively. Standard errors are also indicated ($n = 3$).

SAR, another index of fruit sweetness, was higher in sandy soil (E2 and E4). It showed slight variations, depending on irrigation (I , $p < 0.005$), being significantly lower under full irrigation conditions (I99, 26.39). The maximum SAR was recorded for LS1 and HL2 (>30). However, unlike LS1, whose sweetness is attributable to high TSS, the high SAR of HL2, characterized by low TSS levels, is attributable to very low TA. Unlike LS1, the LS2 genotype (‘Pizzutello’) produced fruits with high values for both TSS and TA; the latter component partially masked the fruit’s sweetness. ANOVA revealed a significant ‘ $E \times I \times G$ ’ ($p < 0.001$) (Figure 7). MP and HL1 genotypes showed consistent SAR values across all environments at water regimes. Other genotypes (e.g., HL2) exhibited lower SAR under full irrigation, whereas the two old long shelf-life genotypes (LS1 and LS2) responded differently to irrigation, depending on the environment.

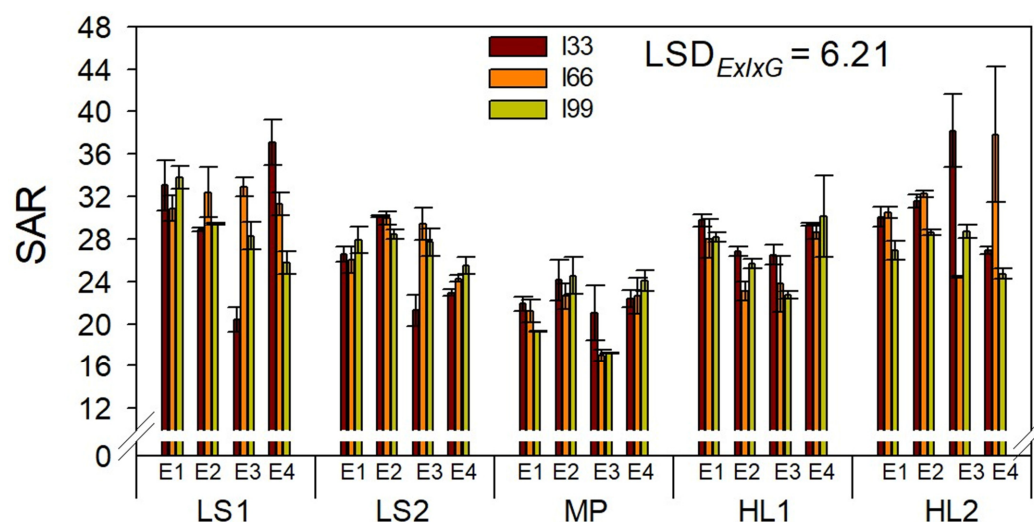


Figure 7. Effect of interaction ‘environment × irrigation × genotype’ ($E \times I \times G$) on SAR in tomato (I33, I66, I99: 33, 66, 99% ETc restoration, respectively). Genotype and environment codes are those reported in Tables 2 and 4, respectively. Standard errors are also indicated ($n = 3$).

3.4. Antioxidant Traits

Antioxidants (ascorbic acid—AscA; total phenols—TPs; flavonoids—Flavs; lycopene—Lyco; antioxidant activity—AA) were also measured in the laboratory.

Unlike sensory traits, the ‘environment’ factor was the primary contributor (~90%) to the total variance in AscA. The highest levels ($>34 \text{ mg } 100 \text{ g}^{-1}$) were measured in E1 (first year, clayey soil) (Table 8). A low irrigation level resulted in a significant increase (+5%) in AscA in fruits from treatment I33 compared to those from I99. Among the cultivars, the two high-lycopene tomatoes (HL1 and HL2) were the richest in AscA, with values exceeding $22 \text{ mg } 100 \text{ g}^{-1}$; the cultivars with the lowest levels ($\leq 17 \text{ mg } 100 \text{ g}^{-1}$) were MP and LS2. The significant ‘ $E \times I \times G$ ’ interaction ($p < 0.001$) indicated that the tomato genotypes responded differently to irrigation, depending on the environment. For instance, HL1 showed higher AscA content under low irrigation rates (I33 and I66), in fruits produced in E1, but not in those from the other environments; conversely, cultivar HL2 showed no variation in any of the environments, although the overall content was markedly higher in E1 (Figure 8).

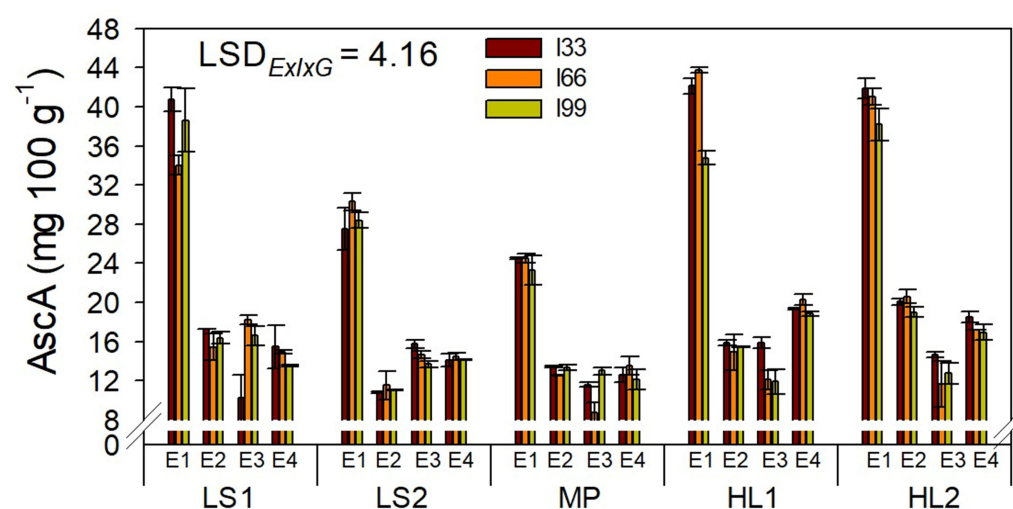


Figure 8. Effect of interaction ‘environment × irrigation × genotype’ ($E \times I \times G$) on the ascorbic acid (AscA) content in tomato (I33, I66, I99: 33, 66, 99% ETc restoration, respectively). Genotype and environment codes are those reported in Tables 2 and 4, respectively. Standard errors are also indicated ($n = 3$).

Table 8. Antioxidants in tomato in relation to *environment (E)*, *irrigation (I)*, and *genotype (G)* (ANOVA) (on a fresh weight basis). AscA: ascorbic acid; TPs: total phenols; Flavs: flavonoids; Lyco: lycopene; AA: antioxidant activity. For the main effects, values (mean $\pm$ SE) followed by the same letter are not significantly different at $p \leq 0.05$ (Tukey's test). Genotype and environment codes are those reported in Tables 2 and 4, respectively.

Main Effect		AscA (mg ascorbic a. 100 g ⁻¹)	TPs (mg GAE 100 g ⁻¹)	Flavs (mg RE 100 g ⁻¹)	Lyco (mg 100 g ⁻¹)	AA (% Scavenging Activity)
Environment (E)	E1	34.25 $\pm$ 1.10 a	54.19 $\pm$ 1.03 c	14.55 $\pm$ 0.82 b	10.78 $\pm$ 0.80 b	74.83 $\pm$ 0.57 b
	E2	15.17 $\pm$ 0.48 b	59.32 $\pm$ 0.90 b	19.92 $\pm$ 1.09 b	10.19 $\pm$ 0.56 b	78.64 $\pm$ 0.59 a
	E3	13.42 $\pm$ 0.44 c	60.51 $\pm$ 1.73 b	17.32 $\pm$ 1.03 b	12.30 $\pm$ 0.86 a	75.72 $\pm$ 0.94 b
	E4	15.72 $\pm$ 0.42 b	65.05 $\pm$ 0.88 a	31.38 $\pm$ 0.95 a	12.88 $\pm$ 1.12 a	78.98 $\pm$ 0.56 a
Irrigation (I)	I33	20.11 $\pm$ 1.31 a	63.67 $\pm$ 1.12 a	24.14 $\pm$ 1.21 a	10.73 $\pm$ 0.71 c	79.72 $\pm$ 0.55 a
	I66	19.72 $\pm$ 1.28 ab	59.41 $\pm$ 1.07 b	20.05 $\pm$ 1.22 b	11.48 $\pm$ 0.72 b	76.71 $\pm$ 0.64 b
	I99 (control)	19.09 $\pm$ 1.14 b	56.23 $\pm$ 1.01 c	18.19 $\pm$ 0.97 b	12.41 $\pm$ 0.81 a	74.70 $\pm$ 0.53 c
Genotype (G)	LS1	20.95 $\pm$ 1.73 b	64.28 $\pm$ 1.12 a	22.92 $\pm$ 1.12 b	11.63 $\pm$ 0.61 c	79.35 $\pm$ 0.53 a
	LS2	17.19 $\pm$ 1.18 c	65.72 $\pm$ 1.36 a	27.03 $\pm$ 1.49 a	6.47 $\pm$ 0.17 d	79.94 $\pm$ 0.61 a
	MP	15.26 $\pm$ 0.91 d	53.33 $\pm$ 1.25 c	16.73 $\pm$ 1.09 c	5.40 $\pm$ 0.25 e	73.22 $\pm$ 0.51 d
	HL1	22.10 $\pm$ 1.86 ab	55.83 $\pm$ 1.30 c	15.21 $\pm$ 1.36 c	17.69 $\pm$ 0.64 a	75.42 $\pm$ 0.95 c
	HL2	22.71 $\pm$ 1.80 a	59.09 $\pm$ 1.24 b	22.08 $\pm$ 1.63 b	16.49 $\pm$ 0.57 b	77.27 $\pm$ 0.85 b
Significance	E	***	***	***	***	***
	I	**	***	***	***	***
	G	***	***	***	***	***
	E $\times$ I	*	***	***	***	***
	E $\times$ G	***	***	***	***	**
	I $\times$ G	**	ns	***	***	**
	E $\times$ I $\times$ G	***	ns	***	***	ns

Significant at $p \leq 0.05$ (*), 0.01 (**), and 0.001 (***), ns: not significant.

Across water regimes and cultivars, TPs were significantly higher (>65 mg GAE 100 g⁻¹) in fruits produced in E4, whereas a 17% lower content was found in fruits produced in E1. Across environments and cultivars, a 13% increase in TPs was observed as irrigation volume was reduced from 99 to 33% ETc (I , $p < 0.001$). The highest TPs were recorded in the two local landraces (LS1 and LS2) (TPs > 64 mg 100 g⁻¹), while lower content was found in the 'Febo' mini-plum tomato (MP) (TPs < 56 mg). Across water regimes, TPs changed depending on the tomato genotypes and the environment ($E \times G$, $p < 0.001$) (Figure 9A). Overall, the highest TP contents were measured in the two long shelf-life types in environments E1 and E3. In environments E2 and E4, these significant differences persisted only in comparison to the mini-plum type (MP). ANOVA also revealed a significant ' $E \times I$ ' interaction ($p < 0.001$): while TP content in E2 did not vary according to the water regime, greater TPs were recorded in environments E1, E3, and E4 for fruits produced under severe water deficit conditions (I33), although this effect was more pronounced in E3 (Figure 9B).

Overall, flavonoid (Flav) levels followed the same trend as TP levels. Their content was significantly higher in E4 (<30 mg RE 100 g⁻¹) and decreased by 25% as the irrigation rate increased from 33 to 99%. Among the cultivars, LS2 (local 'Pizzutello', >27 mg 100 g⁻¹) was the richest in flavonoids, while MP ('Febo') and HL1 ('Lycomech') were the poorest (<17 mg) (G , $p < 0.001$). Unlike TPs, the three experimental factors interacted significantly on the content of these antioxidants ($E \times I \times G$, $p < 0.001$). Some cultivars (e.g., LS1) did not alter their flavonoid content in response to irrigation across the different environments, also exhibiting greater stability (content remained unchanged over the two years at the same site); conversely, other cultivars (e.g., HL1) responded differently to irrigation levels, depending on the environment, showing higher content under the low irrigation rate (I33) in environment E1, but not in the others (Figure 10).

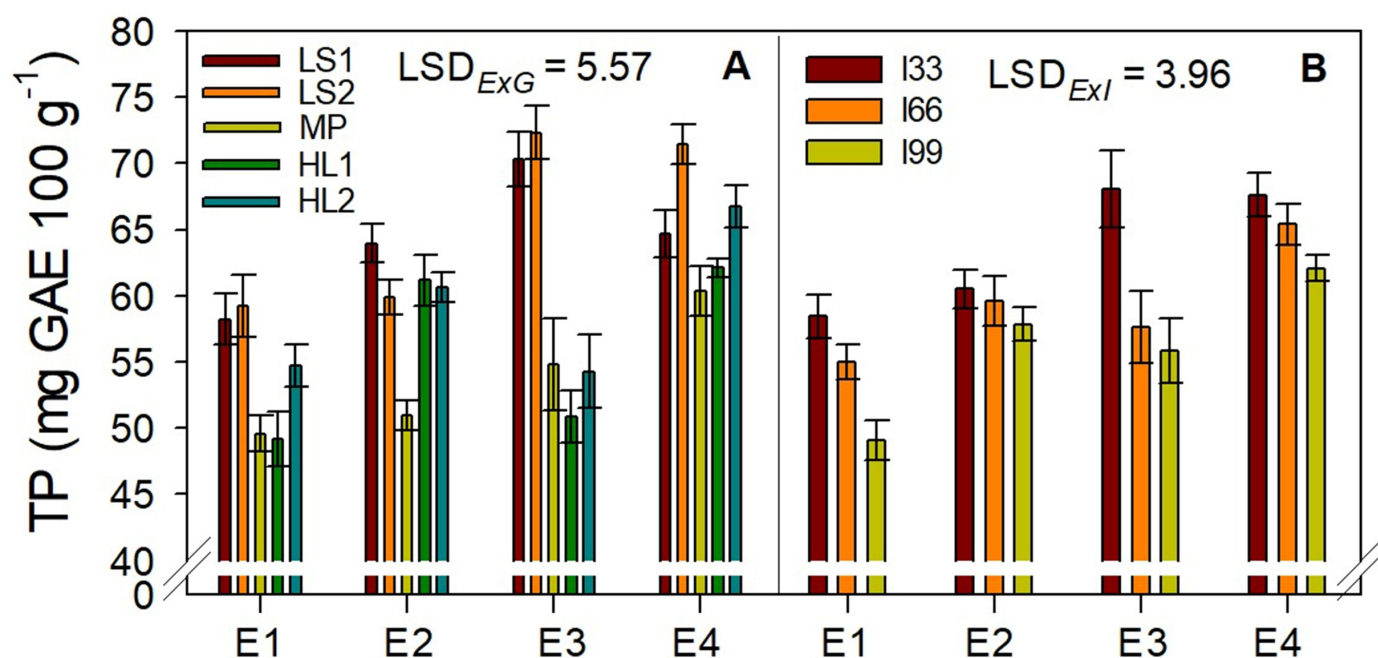


Figure 9. Effect of interaction ‘environment $\times$ genotype’ ($E \times G$) (A), and interaction ‘environment $\times$ irrigation’ ($E \times I$) (B) on total phenol (TP) content in tomato (I33, I66, I99: 33, 66, 99% ETC restoration, respectively). Genotype and environment codes are those reported in Tables 2 and 4, respectively. Standard errors are also indicated ($E \times G$, $n = 9$; $E \times I$, $n = 15$).

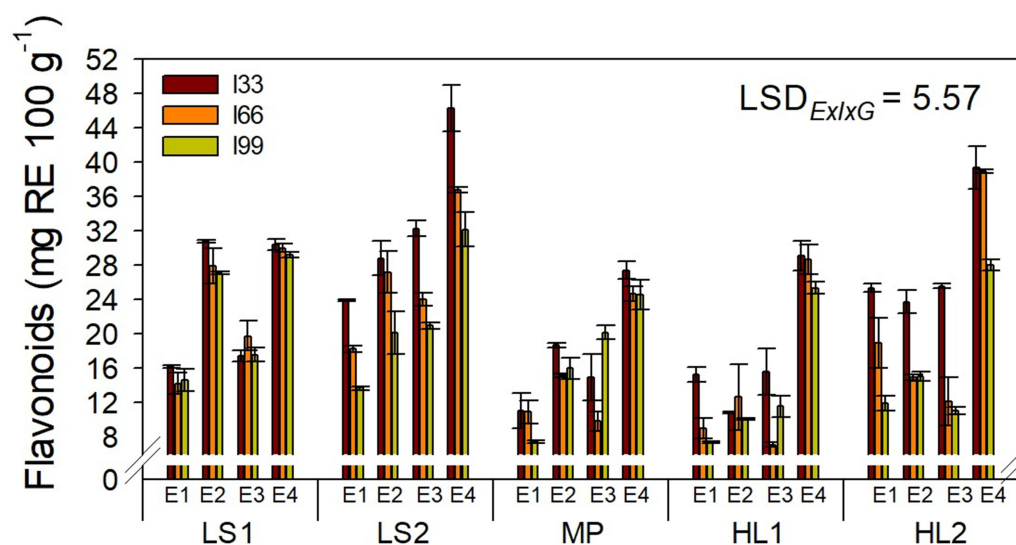


Figure 10. Effect of interaction ‘environment $\times$ irrigation $\times$ genotype’ ($E \times I \times G$) on the content of flavonoids in tomato (I33, I66, I99: 33, 66, 99% ETC restoration, respectively). Genotype and environment codes are those reported in Tables 2 and 4, respectively. Standard errors are also indicated ($n = 3$).

As with the other antioxidants, lycopene (Lyco) content was influenced by all experimental factors. ‘Genotype’ contributed more to the total variance of Lyco (85%) than did ‘environment’ or ‘irrigation’. The levels of this carotenoid were highest ($>12.39 \text{ mg } 100 \text{ g}^{-1}$) in environments E2 and E3 (second season) and were negatively affected by deficit irrigation in treatments I33 and I66 (-14 and -7% lycopene, respectively), indicating that lycopene tends to accumulate to a greater extent in fruits produced under conditions of good soil water availability. As expected, the high-lycopene tomatoes (HL1 and HL2) showed the highest content ($>16 \text{ mg}$), whereas lower levels were detected in the ‘Febo’ mini-plum

tomato (MP) (<6 mg). The three experimental factors interacted significantly on fruit lycopene content ($'E \times I \times G'$, $p < 0.001$). For instance, the local tomato 'Pizzutello' (LS2) exhibited consistent lycopene levels across all environments and water regimes. Interestingly, in environment E3 (clayey soil, second season), this local tomato achieved lycopene levels approaching those measured in the high-lycopene cultivars (HL1 and HL2) under the same environmental conditions. Conversely, in the high-lycopene cultivar 'Lycostar' (HL2), marked differences in lycopene content among water regimes—showing a positive response to irrigation—were observed in environments E1 and E4, but not in environments E2 and E3 (Figure 11).

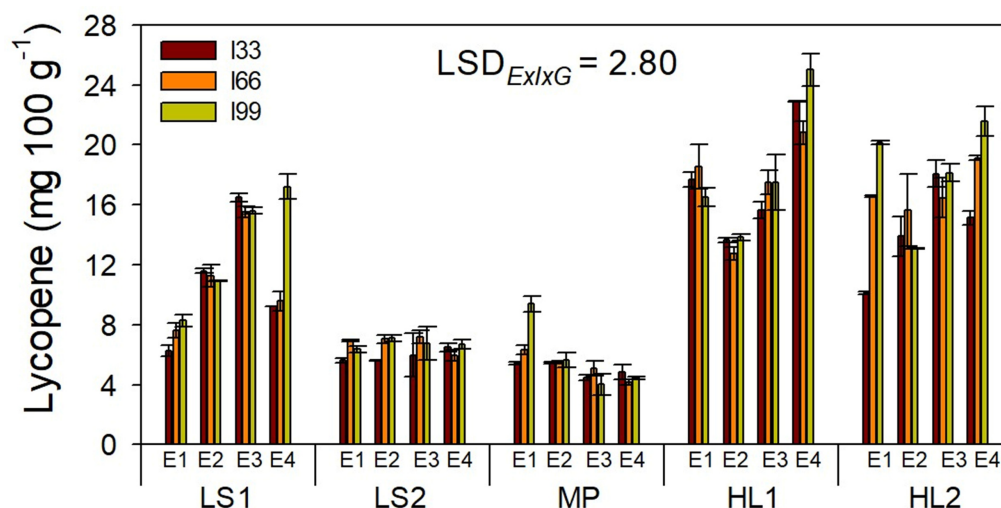


Figure 11. Effect of interaction 'environment $\times$ irrigation $\times$ genotype' ($E \times I \times G$) on the content of lycopene in tomato (I33, I66, I99: 33, 66, 99% ETC restoration, respectively). Genotype and environment codes are those reported in Tables 2 and 4, respectively. Standard errors are also indicated ($n = 3$).

The significant effects of the experimental factors on all antioxidants measured in this study also resulted in significant effects on the antioxidant activity (AA) of the tomatoes. The latter was highest (>78%) in E1 and E4 (sandy soil, first and second seasons). A progressive and significant increase in AA (from 74 to 79%) was observed as the ETC restoration rate was reduced from 99 to 33%. Among the genotypes, the two local tomatoes (LS1 and LS2) exhibited the highest AA (>79%). Lower antioxidant activity (73.22%) was recorded in the fruits of the mini-plum tomato (MP, 'Febo'). ANOVA analysis revealed several significant combined effects of the experimental factors on AA. As observed for TP content, AA varied according to cultivar and environment ($'E \times G'$, $p < 0.001$). Specifically, overall higher antioxidant activity was measured in the two local tomatoes (LS1 and LS2), in environments E1 and E3 (Figure 12A), whereas in environments E2 and E4, significant differences were observed only compared to mini-plum (MP). The significant $'E \times I'$ interaction further revealed that, under conditions of reduced soil water availability (I33), the scavenging activity of the tomatoes was significantly higher than that of fruits produced under the I66 and I99 regimes, in environments E1 and E3; conversely, in environments E2 and E4, differences were significant only compared to the AA measured under the I99 regime (Figure 12B). Unlike TPs, ANOVA revealed a significant $'I \times G'$ interaction, indicating that AA was higher under low soil water content (I33) for all cultivars, except for the mini-plum tomato (MP), for which no differences among the irrigation regimes were detected. Furthermore, cultivars HL1 and HL2 exhibited similar AA levels when grown under deficit irrigation regimes (I33 and I66); however, under optimal irrigation (I99), fruits of HL1 showed significantly lower AA levels than those of HL2 (Figure 12C).

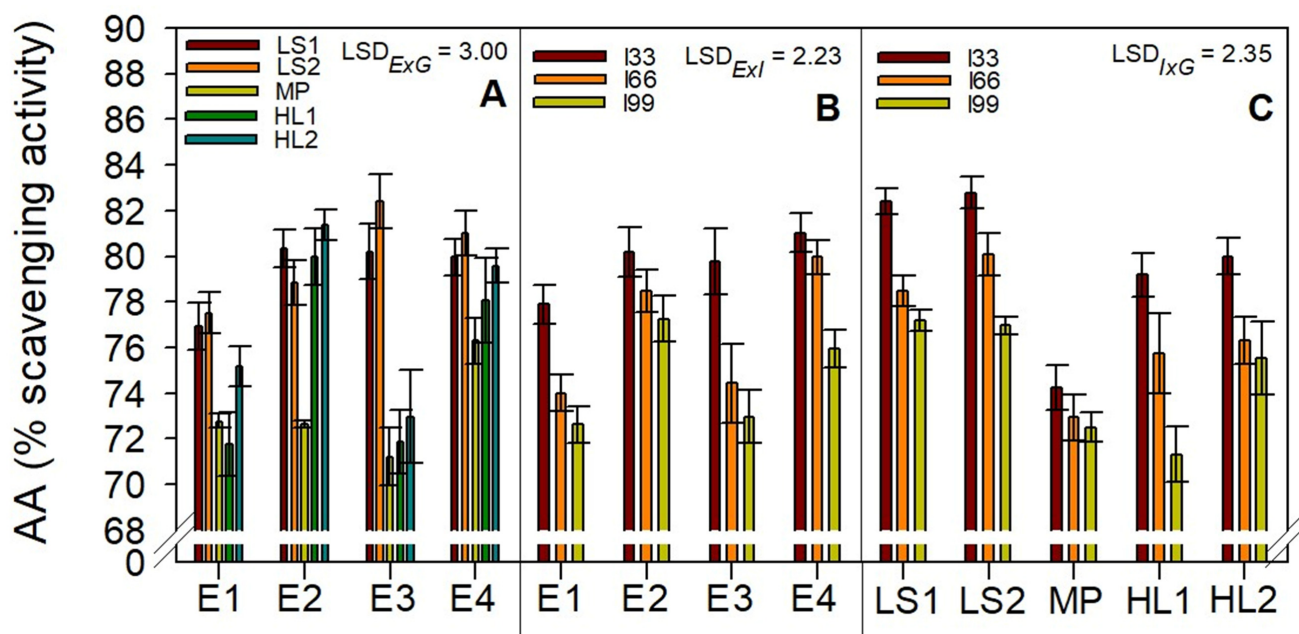


Figure 12. Effect of interaction ‘environment $\times$ genotype’ ($E \times G$) (A), interaction ‘environment $\times$ irrigation’ ($E \times I$) (B), and interaction ‘irrigation $\times$ genotype’ ($I \times G$) (C) on the antioxidant activity (AA) in tomato (I33, I66, I99: 33, 66, 99% ETC restoration, respectively). Genotype and environment codes are those reported in Tables 2 and 4, respectively. Standard errors are also indicated ($E \times G$, $n = 9$; $E \times I$, $n = 15$; $I \times G$, $n = 12$).

3.5. Pearson’s Correlation Analysis

Pearson’s correlation analysis of the measured parameters revealed interesting relationships among them (Table 9). As expected, total fruit yield was negatively correlated with most of the fruit’s sensory and antioxidant components. Specifically, highly significant negative correlations ($p < 0.001$) were observed between FY vs. TS ($r = -0.54$), TSS ($r = -0.69$), RSs ($r = -0.67$), and AA ($r = -0.56$). Certain sensory parameters (TS, TSS, TA) showed positive correlation with antioxidants such as TPs and Flavs, and negative correlation with Lyco and AscA. Furthermore, an increase in Lyco content corresponded to a decrease in fruit TA ($r = -0.76$). The highly significant negative correlation between SAR and TA ($r = -0.71$), and the non-significant correlation with RSs ($r = 0.23$ ns), indicate that titratable acidity, rather than reducing sugar content, may have influenced the sensory attribute of sweetness. Positive correlations of AA vs. TPs and Flavs, but not vs. AscA and Lyco, were found.

Table 9. Pearson’s correlation analysis for the measured traits in tomato ($n = 60$; $\alpha_{0.05} = 0.250$; $\alpha_{0.01} = 0.325$; $\alpha_{0.001} = 0.408$). FY: fresh yield; TS: totals solids; TSS: soluble solids; TA: titratable acidity; RSs: reducing sugars; SAR: TSS/TA; AscA: ascorbic acid; TPs: total phenols; Flavs: flavonoids; Lyco: lycopene; AA: antioxidant.

	FY	TS	TSS	TA	RSs	SAR	AscA	TPs	Flavs	Lyco
TS	−0.54 ***	−								
TSS	−0.69 ***	0.94 ***	−							
TA	−0.12 ns	0.51 ***	0.51 ***	−						
RSs	−0.67 ***	0.65 ***	0.76 ***	0.24 ns	−					
SAR	−0.41 ***	0.19 ns	0.23 ns	−0.71 ***	0.35 **	−				
AscA	−0.08 ns	−0.31 *	−0.13 ns	−0.41 ***	0.28 *	0.34 *	−			
TPs	−0.26 *	0.68 ***	0.61 ***	0.26 *	0.41 ***	0.24 ns	−0.35 **	−		
Flavs	−0.33 **	0.70 ***	0.67 ***	0.29 *	0.32 *	0.26 *	−0.33 **	0.75 ***	−	
Lyco	0.22 ns	−0.41 ***	−0.44 ***	−0.76 ***	−0.42 ***	0.50 ***	0.19 ns	−0.03 ns	−0.02 ns	−
AA	−0.56 ***	0.65 ***	0.65 ***	0.09 ns	0.58 ***	0.43 ***	−0.21 ns	0.90 ***	0.64 ***	0.01 ns

Significant at $p \leq 0.05$ (*), 0.01 (**) and 0.001 (***); not significant (ns).

3.6. Principal Component Analysis of (PCA) and K-Means Clustering

A multivariate data analysis was conducted using principal component analysis (PCA) and K-means clustering to evaluate the effects of experimental factors on the examined traits and to identify potential clusters based on similarity. To simplify the reading and interpretation of the different clusterings, three distinct PCA analyses were performed, considering (i) $E \times G$ (across irrigation levels); (ii) $I \times G$ (across environments); and (iii) $E \times I$ (across genotypes). In all PC analyses, the two principal components (PC1 and PC2) together explained over 70% of the total variation and were used to interpret the distribution of variability. In each biplot, the vector length indicates the magnitude of the variable's contribution to the principal component.

3.6.1. PCA ' $E \times G$ '

PCA ' $E \times G$ ' identified two factors (PC1 and PC2) that together explained 73.2% of the variance (Figure 13A) and were used to score the plot.

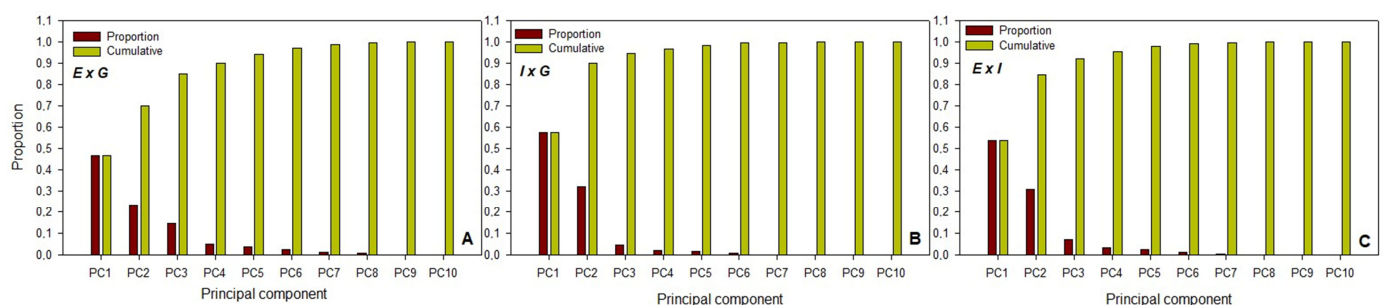


Figure 13. Proportional variance (representing the percentage of variation in dataset) of each component (PC) and cumulative variance in the three PC analyses: *environment* $\times$ *genotype* ((A): $E \times G$), *irrigation* $\times$ *genotype* ((B): $I \times G$), and *environment* $\times$ *irrigation* ((C): $E \times I$).

Positive PC1 was associated with TS, TSS, RSs, TPs, Flavs, and AA, whereas negative PC1 was associated with FY (Table 10; Figure 14A). The variables contributing most significantly to the distinction among treatments were those with the highest loading (eigenvectors) on PC1 and PC2. Therefore, PC1 evidenced a clear gradient between productivity and antioxidant quality, separating high-productive treatments (on the left) from those characterized by high sensory quality and antioxidant content (on the right). PC2 further discriminated treatments based on their nutritional profile, specifically TA, AsCA, and Lyco, whose vectors pointed in opposite directions: positive PC2 indicated high TA, while negative PC2 indicated high levels of AsCA and Lyco. The '*environment*' factor exerted a marked directional effect: environment E3 oriented towards the left (high productivity), while environments E2 and E4 oriented towards the right (high quality); meanwhile, the '*genotype*' factor modulates the response within each specific environment.

The adequacy of the number of clusters in the 'K-means clustering' analysis was evaluated indirectly by measuring the distance of clusters from the centroid. This distance decreases as the number of clusters increases; the optimal number is generally identified at the point beyond which further increases determine only marginal improvements. In this case, this value was 3 (i.e., three clusters), with yield (FY), total phenols (TPs), and flavonoids (Flavs) exerting the greatest discriminating effect. Cluster #1 ($n = 3$ observations) included both the new hybrids (HL) and the mini-plum 'Febo' (MP) from the environment E3, characterized by high fruit yield and low nutritional quality (Table 11). This cluster highlighted highly productive treatments, ideal for quantity-oriented markets or the processing industry. Cluster #2 ($n = 5$ observations) included all genotypes from environment E1, characterized by a balanced sensory and nutritional profile (high RSs, SAR, AsCA, good TPs, and Flavs, but

low FY and Lyco), representing a good compromise between tomato quantity and quality. Cluster #3 ($n = 12$ observations) partly overlapped cluster#2 and included all genotypes from environments E2 and E4 (both on sandy soil) as well as the two local tomatoes (LS1 and LS2) from environment E3; these genotypes exhibited high levels of TS, RSs, SR, TP, Flavs, AA, and Lyco, but low FY, indicating high antioxidant potential. The distribution of treatments in the PCA space is fully consistent with the partition into the three identified clusters.

Table 10. Values of eigenvectors of the first two principal components (PC) in each PCA (FY: fresh yield; TS: totals solids; TSS: soluble solids; TA: titratable acidity; RSs: reducing sugars; SAR: TSS/TA; AscA: ascorbic acid; TP: total phenols; Flavs: flavonoids; Lyco: lycopene; AA: antioxidant activity).

Variable	$E \times G$		$I \times G$		$E \times I$	
	PC1	PC2	PC1	PC2	PC1	PC2
FY	−0.296	0.162	−0.326	0.096	−0.323	−0.290
TS	0.410	0.071	0.373	0.086	0.379	−0.105
TSS	0.419	0.033	0.383	0.073	0.392	0.114
TA	0.203	0.533	0.179	0.459	0.343	−0.237
RSs	0.330	−0.107	0.370	−0.019	0.150	0.480
SAR	0.114	−0.573	0.114	−0.480	0.254	0.373
AscA	−0.108	−0.307	−0.067	−0.513	−0.111	0.417
TPs	0.348	−0.067	0.370	−0.163	0.320	−0.278
Flavs	0.335	−0.047	0.360	−0.100	0.355	−0.210
Lyco	−0.166	−0.452	−0.206	−0.430	−0.087	−0.412
AA	0.364	−0.198	0.337	−0.226	0.382	−0.027

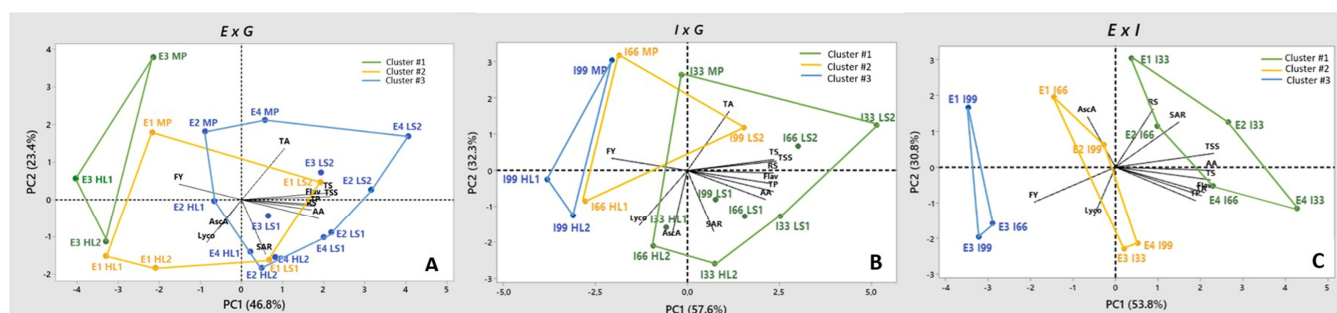


Figure 14. Principal component biplots of PCA for yield and quality traits in tomato (FY: fresh yield; TS: totals solids; TSS: soluble solids; TA: titratable acidity; RSs: reducing sugars; SAR: TSS/TA; AscA: ascorbic acid; TP: total phenols; Flavs: flavonoids; Lyco: lycopene; AA: antioxidant activity) as modulated by environment and genotype ((A): $E \times G$), irrigation and genotype ((B): $I \times G$), and environment and irrigation ((C): $E \times I$). Clusters are also reported within each graph in different colors (K-means clustering).

Table 11. Values of cluster centroids (mean value of each cluster) and grand centroid for each variable in K-means cluster analysis (FY: fresh yield; TS: totals solids; TSS: soluble solids; TA: titratable acidity; RSs: reducing sugars; SAR: TSS/TA; AscA: ascorbic acid; TP: total phenols; Flavs: flavonoids; Lyco: lycopene; AA: antioxidant activity).

Variable	$E \times G$			$I \times G$			$E \times I$			Grand Centroid
	Cluster #1	Cluster #2	Cluster #3	Cluster #1	Cluster #2	Cluster #3	Cluster #1	Cluster #2	Cluster #3	
FY	60.43	37.65	33.61	31.82	44.07	53.69	26.75	38.35	58.86	38.65
TS	7.82	8.66	9.89	9.81	8.92	8.02	9.84	9.14	8.50	9.27
TSS	5.77	6.80	7.36	7.35	6.80	6.06	7.50	6.90	6.25	6.98
TA	0.25	0.25	0.27	0.27	0.28	0.25	0.27	0.27	0.25	0.26
RSs	1.54	2.49	2.32	2.43	2.11	1.86	2.42	2.19	2.03	2.25
SAR	24.41	27.61	27.57	28.58	24.72	25.07	28.28	26.55	25.90	27.11
AscA	12.47	34.25	15.35	20.31	18.13	19.13	19.58	19.62	19.77	19.64
TPs	53.33	54.19	63.70	63.01	56.62	53.20	62.32	60.75	54.20	59.77
Flavs	14.20	14.55	25.04	23.73	17.07	15.71	25.35	20.24	13.94	20.79
Lyco	12.99	10.78	11.49	11.26	9.80	14.10	10.62	12.11	12.30	11.54
AA	72.00	74.83	79.22	78.96	75.21	73.11	79.50	76.75	73.33	77.04

3.6.2. PCA ' $I \times G$ '

PCA ' $I \times G$ ' explained nearly 90% of the total variance through the first two components (PC1 and PC2). Variability decreased significantly after the first two PCs (Figure 13B). PC1 was positively associated with RSs, TSS, TPs, Flavs, and AA, and negatively with FY; therefore, PC1 clearly separates yield-oriented treatments (on the left) from high-quality ones (on the right) (Figure 14B). PC2 separated the treatments based on a small group of traits: TA, AscA, and Lyco content. As in the previous PCA, TA and Lyco showed vectors pointing in opposite directions: positive PC2 indicated high TA, whereas negative PC2 indicated high Lyco (and AscA) content.

As for ' $E \times G$ ', the optimal number of clusters, identified via the K-means algorithm for ' $I \times G$ ', was three; FY exerted the greatest discriminating effect, clearly separating the three clusters. TP and Flav contents also proved to be highly discriminating. Conversely, TA and AscA contributed minimally to cluster separation. Cluster #1 ($n = 9$ observations), located predominantly in the positive region of PC1, included all genotypes from treatment I33, LS and HL2 from treatment I66, and LS1 from treatment I99; it was characterized by high levels of RSs, TPs, Flavs, and AA, but low FY. Thus, this cluster identified a distinct group of treatments with a high-quality profile but reduced productivity. Conversely, cluster #3 ($n = 3$ observations), located on the negative side of PC1, included all genotypes from I99 (with the exception of the two local tomatoes) and exhibited the highest FY and Lyco content, albeit with lower overall quality. This cluster was therefore yield-oriented, with a specific key strength in Lyco content. Cluster #2 ($n = 3$ observations) included MP and HL1 from treatment I66, and LS2 from treatment I99. It shared a nutritional profile similar to that of cluster #3, yet was less yield-oriented and more quality-oriented than the latter. The notable similarity between cluster #2 and #3 suggests a shared quality profile, with minor differences in yield and certain nutritional traits. These differences are attributable to agronomic management (in this case, the irrigation) rather than genotype.

3.6.3. PCA ' $E \times I$ '

PCA ' $E \times I$ ' explained approximately 85% of the total variance through the first two components (PC1 and PC2), which were used to score the plot (Figure 13C). PC1 was positively associated with TA, RSs, SAR, TPs, Flavs, and AA, and negatively with FY, AscA, and Lyco (Figure 14C). Therefore, treatments located on the positive side of PC1 (on the right) exhibited lower yield but high fruit quality; conversely, those on the negative side of PC1 (on the left) were more productive but offered lower fruit quality. Therefore, PC1 splits the different treatments based on yield and nutritional quality.

PC2 discriminates among treatments that promoted sweetness and vitamin C content and those that promoted the accumulation of lycopene and phenols. Indeed, positive PC2 values indicate tomatoes richer in sweetness and AscA, whilst negative values of PC2 indicate tomatoes richer in TA and Lyco. It is interesting to note that the Lyco and RS vectors point in opposite directions (high sugars and low lycopene and vice versa).

The treatments that positively influenced PC1 are those that improved fruit quality while slightly reducing fruit yield. All I33 treatments (very low irrigation rate) are positioned on the right side of PC1. The treatments that negatively influenced PC1 were those that increased fruit yield but diluted sugars and secondary metabolites (total phenols and flavonoids); indeed, most I99 treatments (high irrigation volume) were positioned on the left side of PC1. Treatments that positively influenced PC2 were those promoting the accumulation of sugars and AscA; all irrigation treatments in environments E1 and E2 were positioned on the positive side of PC2 (upper part). Treatments that negatively influenced PC2 were those promoting lycopene and phenol content; in this regard, all

irrigation treatments in environments E3 and E4 were found on the positive side of PC2 (upper part).

As for ' $E \times G$ ' and ' $I \times G$ ', K-means clustering analysis identified three as the optimal number of groups (clusters) for the ' $E \times I$ ' combination. FY contributed significantly to cluster separation. Cluster #1 ($n = 5$ observations), located on the right side of PC1, included treatments with moderate or low irrigation volumes (I66 and I33) across almost all environments; these treatments promoted the accumulation of total phenols and flavonoids as well as antioxidant activity, albeit at the cost of reduced productivity. Cluster #3 aligned with the FY vector (left side of PC1), indicating a group of yield-oriented treatments characterized by high lycopene content but low overall antioxidant value. Cluster #2, positioned between the previous two, included various combinations of environments and irrigation regimes, identifying a group of treatments with a balanced profile (yield/quality trade-off).

4. Discussion

This study was an attempt to characterize tomato genotypes—new, old, and traditional—based on their productivity and their sensory and nutritional profile, as well as to assess their response to deficit irrigation regimes across different semi-arid environments. These environmental conditions were replicated by combining two sites—similar in climatic conditions but differing in soil texture—with two growing seasons (2023 and 2024).

4.1. Environment

The second season (2024) was slightly warmer than the first (2023). This thermal difference between the two seasons, combined with a rainy mid- to late spring in 2023 and a dry one in 2024, may explain the differences in yield and fruit quality observed between the two years. A cropping-season dependence was also reported in tomato genotypes cultivated under climatic conditions similar to those of the present study [9].

Thermal differences were also noted between the two sites, with slightly higher minimum and maximum temperatures at Site2 (sandy soil). The variation in atmospheric conditions between the two sites may have influenced tomato plant physiology and, ultimately, fruit yield and quality, even under full irrigation [12].

Soil texture also influenced both yield and tomato quality characteristics, accounting for over 85% of the total variance in fruit yield. Productivity was lower at the site with sandy soil (E2 and E4); conversely, overall fruit quality was superior in sandy soil. A previous study on tomato highlighted how the poor water retention of sandy soils led to reduced growth and lower fruit yield compared to clayey soil. In contrast, the higher water retention of clayey soil resulted in greater shoot fresh and dry weight, a higher number and weight of fruits, and a higher overall yield [25]. In our study, the poor water retention of sandy soil in the root zone may have caused plant stress, despite adequate water availability. Indeed, even with high irrigation volumes (I99), the soil water deficit in E4 (sandy texture) frequently dropped below the irrigation threshold—reaching peaks of 90% (Figure 2)—thereby likely causing water stress. This was likely attributable to the fact that the volume of water applied with irrigation was calculated indirectly based on ETc rather than on the actual soil water content at the time of irrigation. More frequent irrigation in sandy soils could mitigate this issue. In general, plants subjected to water stress produce higher-quality fruits, primarily due to lower fruit water content and higher concentration of solutes and secondary metabolites [26].

4.2. Irrigation

In the semi-arid cultivation areas of the Mediterranean region, field-grown tomatoes are cultivated during the summer season, thereby requiring large amounts of irrigation

water [12]. In such areas, deficit irrigation can be a viable option for reducing water consumption and improving crop sustainability. Deficit irrigation (DI) is a water-saving strategy that involves the deliberate application of sub-optimal water levels to the crop, limiting yield losses while significantly improving fruit characteristics [27]. Numerous studies have demonstrated the validity of adopting DI in tomato cultivation [12,27]. However, the level of DI can significantly influence both crop yield and fruit quality traits [28]; it is therefore crucial to identify the most suitable DI strategy for each genotype and growing environment [29]. In the present study, DI was applied at two different levels (66 and 33% of ET_c restoration) throughout the entire crop cycle. As expected, fruit yield was higher under full irrigation conditions (99% of ET_c restoration), whereas severe DI (33% ET_c restoration) resulted in an average yield loss of 42%. However, this loss was reduced to 19% by adopting moderate DI (66% ET_c restoration), while simultaneously achieving water savings of 27–28% and an 11% increase in water productivity (rising from 12.54 to 13.90 kg m⁻³)—a parameter calculated as the ratio of fruit yield to the volume of irrigation water applied. Furthermore, the DI regimes resulted in a significant improvement in sensory quality traits (total soluble solids, reducing sugars, total soluble solids to titratable acidity ratio) and antioxidant properties (total phenols, vitamin C, antioxidant activity), with significant positive effects on consumer acceptability. These results are consistent with the literature [30,31], which reported a significant improvement in tomato fruit quality following a reduction in irrigation input. In contrast, in the present study, the crop did not benefit from DI in terms of lycopene accumulation, which was reduced under low irrigation conditions. Similar negative effects of water deficit on lycopene content have been reported in other studies [32]. Based on these findings, DI with 66% ET_c restoration may represent a good compromise between yield and quality in tomatoes. A previous study on the same crop indicated that subjecting plants to water stress by maintaining soil moisture between 60 and 70% of field capacity optimized both yield and fruit quality [33].

4.3. Genotype

In this study, ‘genotype’ contributed more to the total variance in sensory quality than did ‘environment’ or ‘irrigation’. Indeed, marked differences in yield and quality were observed among the tomato genotypes. As reported in previous studies [10,34], local tomato landraces showed lower productivity than hybrids, having never undergone genetic improvement for this trait [35]. However, the high variability in agronomic traits—including plant productivity—previously observed in a large group of these local landraces, confirmed the potential to select for specific desired characteristics from among them [10,36]. In the present study, of the two local types, the one from the Aeolian island of ‘Vulcano’ exhibited greater stability than ‘Pizzutello’ and all hybrids in response to reduced water supply, showing minimal variations in yield and fruit quality (particularly sensory quality) under DI conditions. Long shelf-life tomatoes are traditionally irrigated until the plants are established, after which irrigation is suspended [10]; the limited response to increased irrigation levels observed in the ‘Vulcano’ genotype indicated greater drought resilience in this tomato. A similarly low response to irrigation, compared to other local landraces, had previously been reported for this landrace [37]. Only fruit lycopene content benefited from high irrigation levels, suggesting that water management for this genotype could be adjusted based on quality expectation (high sensory quality *versus* high antioxidant quality). The ‘Vulcano’ landrace also showed less sensitivity to environmental fluctuations than the other tomatoes, maintaining its sensory quality virtually unchanged. In this regard, this tomato is a promising candidate for introduction into low-input cropping systems, as it is expected to outperform new hybrids under limited water conditions.

Overall, both local landraces exhibited superior sensory quality compared to the hybrids and stood out for their phenolic content. This trait is ascribed to environmental pressure, which favors the selection of genotypes with higher phenolic levels—compounds used as a defense mechanism to survive the severe soil water deficits [38]—typical of long shelf-life tomato cultivation. As expected, the high-lycopene cultivars produced fruits richer in this carotenoid, although the differences compared to the local landrace ‘Vulcano’ disappeared under specific environmental conditions (specifically, at a clayey-soil site during the second season of the experiment).

4.4. Pearson’s Correlation

This study describes interesting correlations among all the traits examined. As previously reported for tomatoes grown in a semi-arid area of the Mediterranean region [9], fruit yield was negatively correlated with fruit sensory quality; this indicates that agronomic practices (e.g., irrigation) that boost plant productivity result in lower overall fruit quality. Among the antioxidants, TPs and Flavs—but not Lyco and AscA—were positively correlated with AA, confirming the findings of Patanè et al. [9] that antioxidant activity in tomato fruits can be associated with total phenol and flavonoid content. Consistent with a previous study, a positive correlation was observed between TSS and AscA, a finding attributable to the role of soluble hexoses as precursors in ascorbate synthesis [39].

4.5. Multivariate Analysis

In this study, a multivariate data analysis was performed using a principal component analysis (PCA), with the first two components (PC1 and PC2) capturing both genotypic and phenotypic variability. In an agronomic context, the distance of a specific treatment from the origin in the PCA plot measures the treatment’s agronomic impact (i.e., the extent to which it differs from the average), by considering the measured variables all together; the greater the distance from the origin (i.e., the deviation from the average treatment), the more pronounced the treatment’s agronomic response (or its influence on one or more variables), and vice versa [40]. Regarding the combination ‘*environment* × *genotype*’, certain combinations in environment E3 (clayey soil in the second season) showed superior performance in terms of fruit yield, whereas those in environments E2 and E4 (both on sandy soil) exhibited superior quality traits. Furthermore, all treatments involving the local ‘Vulcano’ tomato clustered relatively close to the origin (i.e., the mean profile of all samples), indicating a minor response to the environment and, consequently, greater stability for this tomato (dominance of ‘*genotype*’ over ‘*phenotype*’). The other local tomato (‘Pizzutello’) exhibited similar stability, but only at the clayey-soil site. Conversely, all the hybrids (mini-plum and new high-lycopene hybrids) were positioned at a considerable distance from the origin when grown on clayey soil, highlighting a highly variable agronomic response to this environment (dominance of ‘*phenotype*’ over ‘*genotype*’). Similarly, regarding the combination ‘*irrigation* × *genotype*’, it is interesting to note how both local tomatoes progressively move away from the origin as the irrigation volume decreases; this indicates that, when irrigated, they partially lose their characteristic sensory and nutritional traits, shifting towards the average profile. The opposite behavior was observed for the hybrids, which, under conditions of reduced soil water availability (I33), shifted towards the origin, positioning themselves close to local tomatoes under high and moderate irrigation rates (I99 and I66, respectively).

In turn, the length of each variable’s vector indicates the magnitude of its variability: the longer the vector, the greater the variability, and vice versa [40]. Thus, the vectors reveal the contribution of different traits to overall variability, discriminating among treatments to a lesser (short vectors) or greater (long vectors) extent. In this regard, sensory traits such

as TA and SAR, and antioxidant traits such as AscA and Lyco, displaying long vectors in the '*irrigation* × *genotype*' PCA, demonstrated a strong capacity to discriminate among treatments, clearly separating old tomato cultivars (regardless of the irrigation regime) from hybrids grown under conditions of high water availability. These results highlighted that the old local tomatoes, commonly cultivated under conditions of low water availability, retain distinctive sensory and nutritional characteristics compared to hybrids, even when adequately irrigated (I99 treatment).

The various combinations of experimental factors (*environment*, *irrigation*, *genotype*) were grouped using K-means clustering based on their similarity. These groupings provided insights into how different tomato cultivars responded to cultivation conditions, allowing for a better understanding of the extent to which genotype might prevail over phenotype in this response. Indeed, the response of the different cultivars to irrigation varied depending on environmental factors (specifically, soil type and growing season). For each combination of experimental factors ('*environment* × *genotype*', '*irrigation* × *genotype*', and '*environment* × *irrigation*'), three distinct treatment groups were identified using PCA and K-means clustering, highlighting similarities among treatments within each cluster. While some combinations fell entirely within a single cluster—suggesting distinct, stable, and predictable performance—others were distributed across two overlapping clusters, i.e., thereby exhibiting characteristics of both. This overlap reveals inconsistent treatment behavior, indicating lower reliability for these combinations. For instance, in the PCA for '*environment* × *genotype*', environment E1 (clayey soil in the first season) predominated in cluster #2 (which included all cultivars); however, the two local tomatoes were positioned in a cluster area that overlapped with cluster #3, indicating that, in this environment, they possessed characteristics attributable to both groups. Conversely, all hybrids in E3 (clayey soil in the second season) were clearly grouped into a single cluster (cluster #1), indicating homogeneous behavior in that environment. This was not the case in the '*environment* × *irrigation*' PCA, where the clear separation among all clusters highlighted the distinct agronomic impact of each treatment.

5. Conclusions

In conclusion, this study revealed that, overall, long shelf-life tomato landraces (particularly the one from the 'Vulcano' island) are better adapted to conditions of low soil water availability than the new hybrids. Indeed, in these old cultivars, genotype prevails over phenotype; yield and fruit quality (especially sensory traits) remain more stable across varying environmental conditions or irrigation regimes, while also demonstrating greater drought resilience. In this context, reintroducing old landraces of long shelf-life tomato—which are naturally adapted to low inputs—into existing cropping systems could prove crucial in the face of global climate change. However, deficit irrigation replacing 66% of ETc offers a good compromise between fruit quantity and quality: given the yield characteristics of these old landraces (which typically have lower productivity), this practice can make them economically viable while maintaining high-quality standards.

The new tomato hybrids evaluated in the study showed significant variability in their response to environmental conditions (higher yield in clayey soils, superior quality in sandy soils) and irrigation regimes; this suggests that agronomic management of these tomatoes can be effectively tailored to meet the specific needs—whether regarding quantity or quality—of the end user (processing industry or fresh market).

Breeding for water stress-tolerant cultivars remains a key objective in tomato research; identifying resilient genotypes capable of effectively coping with global climate change is therefore imperative, not only in semi-arid regions but on a global scale.

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