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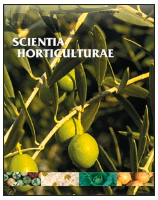

Research Paper

Agronomic performance and characteristics of traditional tomato varieties grown with low input conditions

Alicia Sánchez, Virginia Hernández, Pilar Hellín, Elia Molina, José Fenoll, Pilar Flores *

IMIDA, c/Mayor s/n 30151, Murcia, Spain

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A B S T R A C T

The adaptation to local agro-climatic conditions of traditional varieties renders them a valuable resource for low-input agriculture. This study evaluates the effects of fertilisation (100 % and 50 %) and irrigation (100 % and 75 %) doses on the agronomic performance and fruit quality of traditional tomato varieties. Flor de Baladre (FB), Muchamiel (MC), Pera Pinatar (PP), and Negro de Nerpio (NN) varieties were studied, along with two F1 hybrids (H1 and H2) obtained by crossing NN with other traditional varieties. Mongo (MO) was used as a commercial reference. All traditional cultivars exhibited superior sensory quality and achieved yields similar to MO in the control treatment (7.4 kg plant^{-1}), except for NN (lower number of fruits) and PP (smaller fruit size). FB and MC showed reduced agronomic performance in the treatment combining high fertiliser dose with low irrigation rate (100F+75I), while fruit quality improved due to concentration effects. Despite this, both varieties maintained their yield under reduced fertilisation, with FB further enhancing phenolic compound concentration (17 %). NN and H1 and H2 hybrids showed higher mineral requirements, as their yield was negatively affected by fertiliser reduction. H1 excelled under reduced irrigation treatments, maintaining its yield and improving fructose and phenolic concentration (10 and 11 %, respectively). PP showed tolerance to low in-puts, retaining its yield in all of the treatments and increasing glucose, fructose and vitamin C concentration under reduced fertilisation (12, 8 and 9 %, respectively). The variability of the response of this collection of traditional Spanish varieties represents a valuable resource for sustainable production, being each of the varieties adapted to specific low-input conditions.

Introduction

One of the key challenges that modern agriculture has to face is the environmentally sustainable production of healthy and high-quality food. In particular, the Mediterranean basin, one of the most densely populated and agriculturally important areas in Europe, confronts a high resource consumption due to intensive agriculture, especially in terms of water, energy, and fertilisers (Gao and Giorgi, 2008). This significant demand exerts a considerable pressure on local ecosystems, as the excessive use of water and macronutrients (such as nitrogen, phosphorus, and potassium) can precipitate serious ecological problems, including water scarcity, soil degradation, and contamination of surrounding ecosystems by runoff and leaching, as well as a reduction in agricultural profitability and competitiveness (Kim et al., 2020). The sharp increase in world population, coupled with frequent extreme weather events and environmental pollution, exacerbates the issue of water scarcity (Hein et al., 2021). In this context, attaining a balance between agricultural productivity and environmental protection is vital if the long-term viability of agroecosystems is to be maintained (Tian et al., 2021).

Nitrogen, potassium, and phosphorus are essential macronutrients for crop development. In conventional agriculture, nitrogen is often over-applied to increase yields, though excessive use can negatively affect yield and fruit quality (Albornoz, 2016; Cheng et al., 2021; Elia and Conversa, 2012). The effects of low nitrogen levels on fruit quality are still debated (Bénard et al., 2009; Hernández et al., 2020). Potassium plays a significant role in vegetative growth, yield, fruit quality, and stress resistance (Wang et al., 2013; Li et al., 2021; Liu et al., 2021). Phosphorus is critical for key biological functions such as photosynthesis, respiration, energy transfer, and nucleic acid synthesis (Sung et al., 2015). Along with mineral nutrition, irrigation is a key aspect in agricultural systems. The implementation of effective irrigation management strategies is essential to optimize crop yield and promote efficient use of water, a scarce and vital resource (Wang and Xing 2017; Lu

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* Corresponding author.
E-mail address: mpilar.flores@carm.es (P. Flores).

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et al., 2021). Some studies have demonstrated that reduced irrigation results in a decline in tomato yield, although it does enhance fruit quality by increasing sugar content, titratable acidity, and levels of bioactive compounds such as vitamin C and carotenoids (Conti et al., 2023). Nevertheless, the influence of water deficit on yield and fruit quality characteristics is contingent on the specific tomato genotype.

Following the introduction of tomatoes in Europe in the early 16th century, these fruits spread primarily throughout the Mediterranean countries, leading to the development of a wide diversity of varieties. These were selected by local farmers over generations and are nowadays known as traditional varieties (García-Martínez et al., 2013). In contrast to commercial varieties developed for yield and uniformity, traditional varieties maintain a high genetic diversity and offer exceptional organoleptic qualities, which include a superior taste and aroma. These attributes are becoming increasingly important to consumers and the industry (Casals et al., 2011; Figàs et al., 2015; Sinesio et al., 2021). Zhu et al. (2018) demonstrated how breeding resulted in alterations to the metabolome of tomato fruits, accompanied by a reduction in the number of genetic alleles associated with flavour and nutritional compounds in commercial cultivars. Previous studies have demonstrated the superior organoleptic and nutritional quality of certain traditional varieties compared to commercial ones, particularly in terms of enhanced taste, higher phenolic compound concentrations, and elevated carotenoid levels (Casals et al., 2021; Figàs et al., 2015). Moreover, traditional varieties have attracted attention for their potential contribution to sustainable agriculture, owing to the hypothesis that their evolution within traditional farming systems has conferred adaptations enabling them to perform effectively under resource-limited conditions (Casals et al., 2021). In the context of resource scarcity and increasing demand for sustainable food production, these varieties could offer the potential to reduce inputs such as fertilisers and water without compromising yield or fruit quality. While the performance of commercial tomato varieties under reduced-input conditions has been widely studied (Wang et al., 2019; Wang and Xing, 2017), research on traditional varieties has predominantly focused on their potential in abiotic stresses, such as under salt stress (Massaretto et al., 2018; Meza et al., 2020; Moles et al., 2016), or their suitability for organic management systems (Chea et al., 2021; Suárez et al., 2008). However, only a small subset of the available traditional material has been evaluated, and studies specifically addressing their responses to reduced irrigation and fertilisation remain notably limited.

Previous evaluations of traditional tomato varieties, focusing on both agronomic performance and fruit quality, enabled the identification of cultivars that combine exceptional fruit quality with robust agronomic traits, highlighting their potential for commercial cultivation (Flores et al., 2020, 2017; Hellín et al., 2023; Sánchez et al., 2023). Using these superior cultivars, hybrids were developed to introduce novel genetic combinations (Sánchez et al., 2024). Among the resulting hybrids, those exhibiting yield levels comparable to commercial varieties while retaining or enhancing the fruit quality characteristics of their traditional parental lines were selected for further evaluation.

The objective of this study, corresponding to the second phase of this research, is to evaluate the performance of the selected collection of traditional varieties, characterised by genetic diversity and valuable traits, under low-input conditions, a key factor in the advancement of sustainable agriculture. For that, a 50 % reduction in fertiliser was applied to simulate moderate nutrient stress, sufficient to differentiate tomato variety tolerance without causing crop failure (Wang and Xing, 2017; Abdelhady et al., 2017). Additionally, to assess tolerance to water deficit, irrigation was reduced by 75 % of crop evapotranspiration (ETc), based on studies showing this level induces significant water deficit without severely impacting yield or quality in tolerant genotypes (Wu et al., 2021; Al-Selwey et al., 2021), thereby enabling the identification of varieties with improved adaptation to deficit irrigation. The traits of interest for this evaluation include agronomic performance, organoleptic quality parameters, and the concentration of key bioactive compounds in tomato, such as carotenoids, phenolic compounds, and vitamin C.

Table 1
Main characteristics of the studied cultivars.

Cultivar	Bank code	Type	Colour	Size[x]
MO		Commercial hybrid (Marmande)	Red	L
FB	BGMU0640	Traditional (Flor de Baladre)	Pink	XL
PP	BGMU0683	Traditional (Pera)	Red	M
MC	BGMU0753	Traditional (Muchamiel)	Pink	L
NN	BGMU0922	Traditional (De la Sierra)	Red-Black	L
H1	BGMU0640 x BGMU0922	Experimental hybrid	Red	XL
H2	BGMU0661 x BGMU0922	Experimental hybrid	Red	L

[x] Size corresponds to the following: M (75–150 g), L (150–300 g), and XL (>300 g).

2. Materials and methods

2.1. Plant material

Four traditional tomato varieties from the IMIDA germplasm bank (BAGERIM), previously selected for their agronomic performance and/or high quality (Sánchez et al., 2023), were grown: Flor de Baladre de Espinardo (FB; noted for its strong agronomic performance and exceptional flavour), Pera Pinatar (PP; recognized for its good agronomic performance), Muchamiel (MC; characterized by its agronomic performance and accession variability), and Negro de Nerpio (NN; distinguished by its high lycopene content and remarkable flavour) (Table 1; Fig. 1). Additionally, two experimental F1 hybrids were included: "Flor de Baladre de Espinardo x Negro de Nerpio" (H1) and "Rosa de la Arboleja x Negro de Nerpio" (H2), both previously characterized by their good organoleptic and nutritional characteristics and an acceptable yield (Sánchez et al., 2024). A commercial control variety, Mongo (MO) (Ramiro Arnedo, S.A.), was also included in the study.

2.2. Experimental design and growth conditions

The cultivars described above were grown in a polyethylene multi-tunnel greenhouse at an experimental farm ("Torreblanca") located in Torre Pacheco (Murcia, SE Spain; 37° 46′ 33.564″ N, 0° 53′ 47.225″ W). The area has a Mediterranean climate, and its soil is classified as clay loam. The plants were irrigated with water from the Tajo-Segura transfer system (0.8–1.3 dS m^{-1}). The total amounts of fertilisers (F) applied during the entire growing season at the 100 % fertilisation level (100F) consisted of 175 N, 180 P_2O_5, 276 K_2O, 125 *Ca*, and 30 Mg (kg ha^{-1}). At the 100 % irrigation level (100I), the total water volume applied was 0.24 m^3 m^{-2}. Table 2 provides detailed information regarding the distribution of the total dose of fertiliser and the total irrigation rate across the primary growth phases of the crop cycle. Both conditions were established on the basis of typical cultural practices and soil and climatic conditions of the growing area, as well as following the technical specifications for integrated tomato production, in accordance with the Order of 10 May 2012 (BORM, 2012). Both inputs were supplied through separate irrigation tanks for each treatment, using a drip irrigation system equipped with individual 2 L h^{-1} drippers for each plant. Fertiliser solutions were prepared and applied weekly, ensuring homogeneous distribution. Treatments consisted of a combination of two doses of fertilisation (F), 100 % and 50 %, with two rates of irrigation (I), 100 % and 75 %, resulting in a total of four treatments (100F+100I, 100F+75I, 50F+100I, 50F+75I) (Table 2). Based on the total amounts applied at the control treatment (Table 2), the total 50 % fertilisation dose (50F) corresponded to 87.5 N, 90 P_2O_5, 138 K_2O, 62.5 *Ca*, and 15

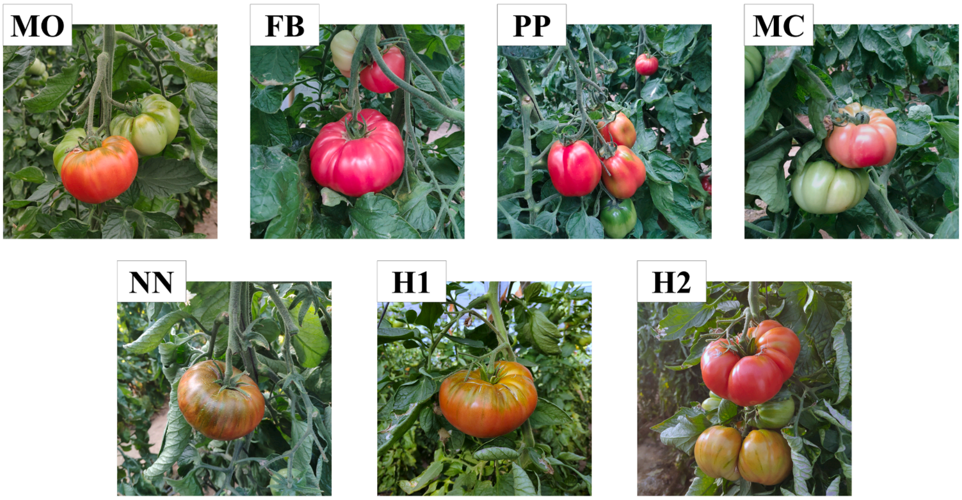

Fig. 1. Images of the studied varieties (Mongo [MO], Flor de Baladre de Espinardo [FB], Pera Pinatar [PP], Muchamiel [MC], and Negro de Nerpio [NN]), and the experimental hybrids H1 and H2.

Table 2
Distribution of nutrients and irrigation throughout the crop growth cycle under the control treatment (100F and 100I). Nutrient values (N, P_2O_5, K_2O, *Ca* and Mg) are expressed as (kg ha^{-1}), and water is expressed as (m^3 m^{-2}).

Growth Phase	N	P_2O_5	K_2O	Ca	Mg	Water
Transplant - Appearance of third truss	15	30	25	5	0	0.02
Ending phase 1 - Colour turn of first fruits	137	120	211	90	25	0.19
Ending phase 2 - End of culture	23	30	40	30	5	0.03
Total crop cycle	**175**	**180**	**276**	**125**	**30**	**0.24**

Mg (kg ha^{-1}). Similarly, the total 75 % irrigation rate (75I) corresponded to a total water volume of 0.18 m^3 m^{-2}. As a result of the decrease in water volume without reducing the fertiliser dose, the irrigation solutions of the 100F+75I and 50F+75I treatments were 33 % more concentrated than those of 100F+100I and 50F+100I, respectively.

Transplant was manually established in December using 40-day-old seedlings sourced from a commercial nursery. The planting frame was 0.44 m between plants and 1 m between rows, resulting in a transplanting density of approximately 2.27 plants per square meter. The experimental design included two randomized blocks per cultivar and treatment, resulting in a total of eight blocks. Within each block, the position of the seven cultivars was also randomized. Each block comprised a single row containing the seven cultivars described above, with five plants per cultivar (a total of 35 plants per block). The total area per block was 15.4 m^2. Boundary rows were placed along the edges of the test area and between the treated rows to avoid a "boundary effect". The plants grew vertically with one stem after axillary bud removal and were maintained until the end of the production phase (200–250 days after transplanting, depending on the genotype). A total of 5–6 trusses were harvested, depending on the variety, and fruits from the 2nd to the 4th truss used for sensory and fruit quality analyses. Integrated pest and disease management was carried out following the technical specifications for integrated tomato production, in accordance with the Order of 10 May 2012 (BORM, 2012). Bumblebee hives were employed to enhance pollination. Temperature evolution during this period is illustrated in Supplementary Figure 1, which shows the hourly average temperature (°C) recorded by the TP42 weather station in the experimental farm of the SIAM (Murcia Agricultural Information System). During the harvest period (from April to July), mean day and night temperatures ranged between 12 and 37 °C and 6–20 °C, respectively.

Table 3
Description and score scale for all of the evaluated traits.

Trait	Description	Scale
Visual		
Colour	Visual evaluation of the optimal skin colour of the tomatoes	0–10
Bicolour	Visual evaluation of two different colours	1–4
Homogeneity	General homogeneity of the sample	0–10
Brightness	Sensory attribute due to the natural waxes in skin of the tomato	1–4
Ribbing	Intensity of the ribs at calyx end	1–4
Green shoulder	Intensity of the green trips at calyx end	1–4
Flavour		
Sweet	A flavour stimulated by sugars	0–10
Acid	A flavour stimulated by acids	0–10
Tomato ID	Aromatics reminiscent tomato characteristic flavour	0–10
Fruity	Aromatics reminiscent fruity flavour	0–10
Aftertaste	Time that the tomato flavour remains in mouth after swallowing	0–10
Texture		
Hardness	Force required to bite completely through the sample with molar teeth	0–10
Crunchiness	Intensity of audible noise at first bite with molars	0–10
Juiciness	Sensation of moisture released by the tomatoes during the first bites	0–10
Juice density	Thickness of the tomato juice during the first bites	1–3
Flesh	Amount of pulp detected in mouth after the first bites	0–10
Peel	Thickness of the pericarp evaluated during the first bite	0–10
Seeds	Quantity of seeds of the sample	0–10
Solubility	Amount of tomato that remains after chewing 5 times	0–10
Residual peel	Amount of skin that remains on the teeth after swallowing the sample	0–10
Residual nerves	Degree of perception of the nerves of the tomato before the product is swallowed	0–10

2.3. Sensory analysis

Sensory analysis was conducted following the methodology described by Hongsoongnern and Chambers IV (2008). A trained panel of 13 participants (9 women and 4 men) aged 24–43 years, carried out the methodology. Prior to the sensory session, references for extreme and intermediate values for each trait were established by consensus using a diverse set of commercial tomato samples. This preliminary step allowed the panel to align their criteria and scoring thresholds. The sensory evaluation was conducted in a single 1.5-hour session with all 13 panellists. For each of the analysis, a set of 10–15 commercially-ripe tomatoes was harvested between the second and fourth truss of each

Table 4

Yield (kg plant^{-1}), mean fruit weight (MFW; g), number of fruits per plant (FN), precocity, temporality (T_{85}), fruit uniformity (CV), total soluble solids (TSS, °Brix), and acidity (g L^{-1}) of the selected varieties grown under control treatment (100F+100I).

Cultivar	Yield	MFW	FN	Precocity	T_{85}	CV	TSS	Acidity
MO	7.4^{bc}	193^{b}	40^{d}	5.1^{bc}	11.6^{b}	0.52^{b}	5.1^{a}	3.6^{a}
FB	7.2^{b}	400^{d}	19^{a}	5.1^{bc}	12.8^{c}	0.52^{b}	5.9^{bc}	4.3^{b}
PP	4.9^{a}	105^{a}	48^{e}	6.3^{d}	12.4^{bc}	0.35^{a}	6.6^{d}	3.7^{a}
MC	7.5^{bc}	234^{b}	37^{cd}	5.6^{c}	12.1^{bc}	0.52^{b}	6.2^{cd}	5.2^{c}
NN	3.9^{a}	227^{b}	18^{a}	4.1^{a}	10.8^{a}	0.61^{b}	5.8^{bc}	4.6^{b}
H1	8.1^{bc}	370^{d}	22^{ab}	5.1^{bc}	11.6^{b}	0.58^{b}	4.6^{a}	3.6^{a}
H2	9.0^{c}	312^{c}	29^{bc}	4.9^{b}	11.9^{b}	0.55^{b}	5.6^{b}	4.6^{b}
	***	***	***	***	***	***	***	***

*** Significant differences between means at a 0.1 % level of probability. Different letters in the same column indicate the presence of significant differences between means according to Duncan's test at the 5 % level. Data are means ± SE ($n = 10$).

variety. Selected fruits were washed with fresh tap water and dried with absorbent paper before analysis. In order to mitigate the impact of bias, the samples were anonymised using a coding system. These samples were then presented to the panellists in a randomised order. Panellists evaluated a set of six visual, five taste, and ten textural traits closely related to tomato consumer preferences, as detailed in Table 3, based on Hongsoongnern and Chambers IV (2008). Visual traits were assessed on whole tomatoes, whereas taste and texture traits were assessed on slices of the same tomatoes. Most of the traits were scored on a numerical scale ranging from 0 to 10 in 0.5-unit increments, with 0 representing no intensity and 10 representing an extremely strong intensity. As per the rest of the traits, they were scored on specific smaller scales agreed by the panellists prior to the analysis.

2.4. *Agronomic and fruit morphology evaluation*

In order to determine the agronomic performance of the genotypes that were studied, all of the fruits from five plants per replicate (ten plants per treatment) were collected and individually weighed. Yield (Y), number of fruits (FN), and mean fruit weight (MFW) were evaluated, and fruit uniformity (assessed by the coefficient of variation of individual fruit weight), precocity (weeks elapsed between transplanting and harvesting of 20 % of the fruit), and temporality (T_{85}; weeks needed to reach an 85 % yield) were calculated.

For fruit characterisation and metabolite analysis, three replicates per row (six per treatment) were established, each replicate consisting of ten fruits from two plants. Equatorial and longitudinal diameters were measured using a Mitutoyo 500–196–30 Digimatic calliper (Kanagawa, Japan), and fruit shape index was calculated as the ratio between both diameters. Fruit firmness was measured using a Bertuzzi FT011 hand penetrometer (T.R. Turoni Srl, Forlì, Italy) with an 8 mm-diameter plunger, being this expressed as kg mm^{-1}.

2.5. *Metabolite analysis*

For metabolite analysis, approximately 15 mature and uniform fruits from the same replicate were cut into small pieces and frozen at −80 °C. Subsequently, they were finely crushed using a Thermomix TM 60 and stored at −80 °C until further analysis. Each analysis was conducted in duplicate to ensure analytical reliability and reproducibility. Total soluble solids (TSS) and acidity were determined by refractive index (expressed as °Brix) using a PAL-1 digital hand-held "pocket" refractometer (Atago, USA) and by automatic titration using a Mettler-Toledo DL15 automatic titrator (Barcelona, Spain), expressed as g of citric acid per L of juice, respectively.

Individual soluble sugars, glucose (GLU), and fructose (FRU), were extracted with deionised water, purified with C18 Sep-Pak cartridges, and subsequently analysed by molecular-exclusion chromatography on an Agilent 1100 liquid chromatograph (Waldbronn, Germany). The device was equipped with an RI detector and a CHO-682 LEAD 300 × 7.8 mm ID CARBOSep column (Concise separations, San Jose, *CA*, USA), utilising deionised water as the mobile phase at a flow rate of 0.4 mL min^{-1} (Flores et al., 2016). Calibration curves were constructed using standard solutions of glucose and fructose (Sigma-Aldrich, Steinheim, Germany) within the range of 0 to 750 mg L^{-1}. Results are expressed as mg g^{-1} of fresh weight (FW).

Vitamin C (ascorbic and dehydroascorbic acids) was extracted with ethylenediaminetetraacetic acid (EDTA), 0.05 % (w/v), and dithiothreitol (Sigma, Steinheim, Germany), and was analysed by high-performance liquid chromatography coupled with tandem mass spectrometry (HPLC-MS-MS) according to the methodology developed by Fenoll et al. (2011). Calibration curves were constructed using standard solutions of ascorbic acid (Sigma-Aldrich, Steinheim, Germany) within the range of 0 to 100 mg L^{-1}. Vitamin C (VC) was quantified as μg g^{-1} FW.

Carotenoids and phenolic compounds were extracted using an acetone-hexane solvent (4:6, v/v). Briefly, following a five-minute shaking period, phase separation was achieved through the application of a 10 min, 12,000 rpm centrifugation process. The analysis of carotenoids was conducted in the solvent phase, following the methodology proposed by Nagata and Yamashita (1992). The absorbance of the acetone-hexane layer was measured at 450 nm using a quartz cuvette and a UV–Vis spectrophotometer. A β-carotene calibration curve, constructed using standard solutions in the range of 0 to 10 mg L^{-1}, was employed to express the total carotenoid content in μg g^{-1} FW. The analysis of phenolic compounds was conducted in the aqueous phase using the Folin and Ciocalteau (1927) method, with gallic acid for calibration (from 0 to 300 mg L^{-1}). Absorbance at 765 nm was measured, and results were expressed as μg gallic acid equivalents (GAE) g^{-1} FW.

2.6. *Statistical analysis*

The results of all the analysis were expressed as mean value ± standard error. Data were statistically analysed using IBM SPSS Statistics 25. Data were first checked for normality using the Shapiro-Wilk test and for homogeneity of variances using the Levene median test. A two-way analysis of variance (ANOVA) was then conducted, followed by Duncan's range test for multiple comparisons to establish significant differences between means with a confidence level of 95 %. Principal component analysis (PCA) was performed on the normalised compositional data using pairwise Euclidean distances between accession means. Eigenvalues and percent variance of each principal component were calculated, as well as the correlation coefficients between compositional traits and principal components.

3. Results and discussion

3.1. *General description of the cultivars*

In the control treatment (100F+100I), the traditional varieties Muchamiel (MC) and Flor de Baladre (FB) exhibited yield values that were comparable to those found in Mongo (MO) (Table 4). These

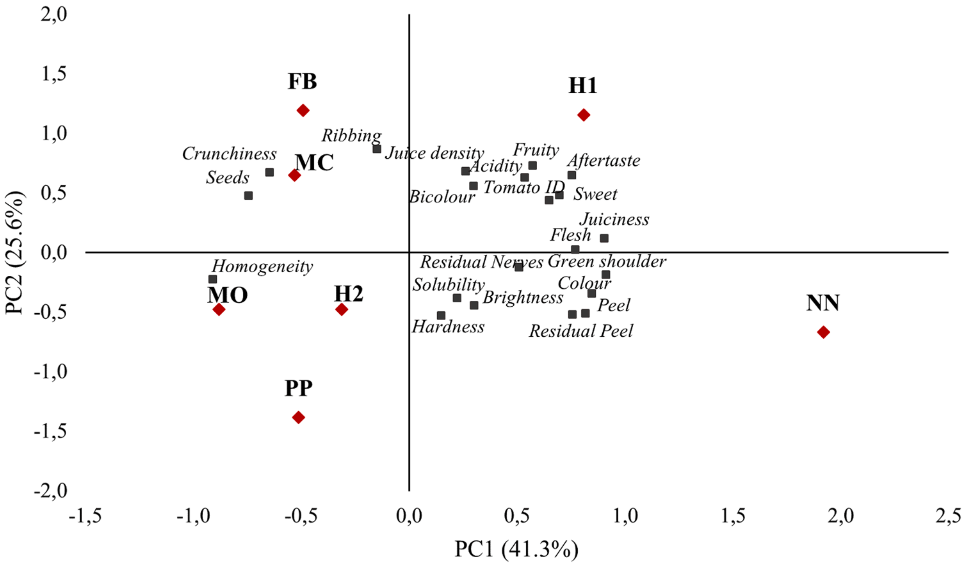

Fig. 2. Bi-plot of the principal component analysis (PCA) of the sensory traits evaluated in the studied cultivars (Mongo [MO], Flor de Baladre [FB], Pera Pinatar [PP], Muchamiel [MC], and Negro de Nerpio [NN]) and the experimental hybrids (H1 and H2).

findings are consistent with those reported by Meza et al. (2020), which demonstrated that, under optimal conditions, certain traditional varieties can match or even surpass commercial varieties in terms of yield. In contrast, despite producing a greater number of fruits per plant, the Pera Pinatar (PP) cultivar exhibited lower yields compared to those found in the commercial variety. This lower yield can be attributed to the smaller fruit size that is characteristic of the PP cultivar. Notwithstanding the high fruit weight of the Negro de Nerpio (NN) variety, its overall yield was low due to the reduced number of fruits per plant. Nevertheless, this variety is highly valued for its fruit quality (Sánchez et al., 2023), which led to its selection as a parent for the development of the H1 and H2 hybrids in the study that was performed by Sánchez et al. (2024). The yield of both hybrids was significantly higher than that of their common parent, NN, and comparable to that of the commercial variety. These results are consistent with the vigour of the hybrids that had been observed in the previous study, which supported their selection as promising varieties.

The parameters of precocity and temporality (T_{85}) provided valuable insights into key factors affecting the profitability of the crop. In order to accurately assess these temporal developmental traits across varieties with differing growth rates, all of the varieties were maintained until the conclusion of the trial, including those that reached maturity earlier. NN was the earliest maturing cultivar, reaching a 20 % yield (precocity) in 4.1 weeks, and showed the lowest T_{85} value (10.8 weeks), which pinpoints a short growing cycle (Table 4). FB, MC, H1, and H2 exhibited a precocity that was similar to that found in the commercial variety MO, with T_{85} values that were comparable, except for FB, which had the highest T_{85} among the studied varieties. The prolonged development cycle of FB presents several disadvantages, including increased resource requirements (fertiliser, water, and labour), a heightened risk of diseases and pests, and a greater exposure to environmental stressors, all of which can negatively impact crop profitability. PP took 6.3 weeks to reach a 20 % production, which made it the last cultivar to do so, whereas its T_{85} was similar to that found in the commercial variety. Regarding fruit uniformity, all of the varieties showed similar CV values, except for PP, which had the lowest one, making it the most homogeneous variety. The uniformity of this fruit, which is often variable in traditional varieties, makes PP particularly noteworthy, since it improves marketability and simplifies harvesting, packaging, and transport.

Regarding fruit composition, all of the varieties showed higher total soluble solids (TSS) and lower acidity compared to the commercial variety, except for the H1 hybrid, which exhibited values that were similar to those observed in Mongo for both parameters (Table 4). The evaluation of commercial tomatoes is largely based on these parameters, and consumers tend to prefer a balance between sweet and sour flavour profiles (Casals et al., 2011). However, overall flavour is influenced by a combination of factors, which does not only include sugars and acids, but also volatile compounds and fruit texture (Felföldi et al., 2021). To evaluate sensory differences, a principal component analysis (PCA) was conducted on the quantitative sensory data. Detailed results are provided in Supplementary Table 1. According to the principle of an eigenvalue greater than 1, the first two components (PC1 and PC2) were used for further comprehensive evaluation. PC1 explained 41.3 % of the total variation, and PC2 explained 25.6 % of it, with a cumulative contribution rate of 66.9 % (Fig. 2). While the H2 hybrid showed intermediate characteristics, the other varieties clustered separately. MO and PP showed negative correlations with PC1 and PC2, indicating a high fruit homogeneity. FB and MC were positively correlated with PC2, signalling an acidic, fruity flavour and ribbed appearance. NN showed a strong positive correlation with PC1, indicating a sweet taste, good aftertaste, juicy texture, green-shouldered appearance, and high skin presence. H1 showed a positive correlation with both PC1 and PC2, and was characterized by acidity, sweetness, aftertaste, fruitiness, and a strong tomato ID.

Several studies comparing the sensory properties of traditional and modern tomato varieties have shown that these varieties, especially the local ones corresponding to southern Italy and eastern Spain, tend to have a higher sensory quality and a higher concentration of aromatic volatiles (Alonso et al., 2009; Casals et al., 2021). However, traditional varieties do not consistently exhibit significantly superior sensory characteristics (Sinesio et al., 2021). To ensure an accurate comparison, it is essential to select an appropriate commercial variety that can be used as a reference. MO was developed through modern breeding to improve consumer-driven quality traits; thus, it serves as an effective reference for comparison with traditional varieties that have previously exhibited a high quality (Flores et al., 2016, 2017; Sánchez et al., 2023, 2024). With regards to this reference, all of the traditional varieties (FB, MC, NN, and PP) that were selected for their outstanding characteristics in a previous study demonstrated superior organoleptic properties in both composition and sensory analyses. In addition, PP stood out for its fruit homogeneity, particularly appreciated in a commercial context (Casals et al., 2011). In spite of having lower TSS and acidity values than the other traditional varieties that were studied, H1 achieved

Table 5

Effect of fertilisation (100 % *vs* 50 %) and irrigation (100 % *vs* 75 %) on yield (Y; kg plant^{-1}), mean fruit weight (MFW; g), and number of fruits (FN) per plant in the studied varieties (Mongo [MO], Flor de Baladre [FB], Pera Pinatar [PP], Muchamiel [MC], and Negro de Nerpio [NN]) and the experimental hybrids (H1 and H2).

	MO			FB			PP			MC			NN			H1			H2		
	F	I	FxI	F	I	FxI	F	I	FxI	F	I	FxI	F	I	FxI	F	I	FxI	F	I	FxI
Y	ns	ns	ns	ns	*	**	ns	ns	ns	ns	ns	ns	*	ns	*	**	ns	ns	**	*	ns
MFW	ns	*	ns	*	*	**	ns	ns	ns	ns	ns	**	ns	ns	ns	ns	ns	ns	ns	ns	ns
FN	ns	*	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns	*	ns	*	ns	ns	ns	*	ns	ns

*, ** Significant differences between means at a 5 or 1 % level of probability, respectively; ns, non-significant at $p = 5$ %.

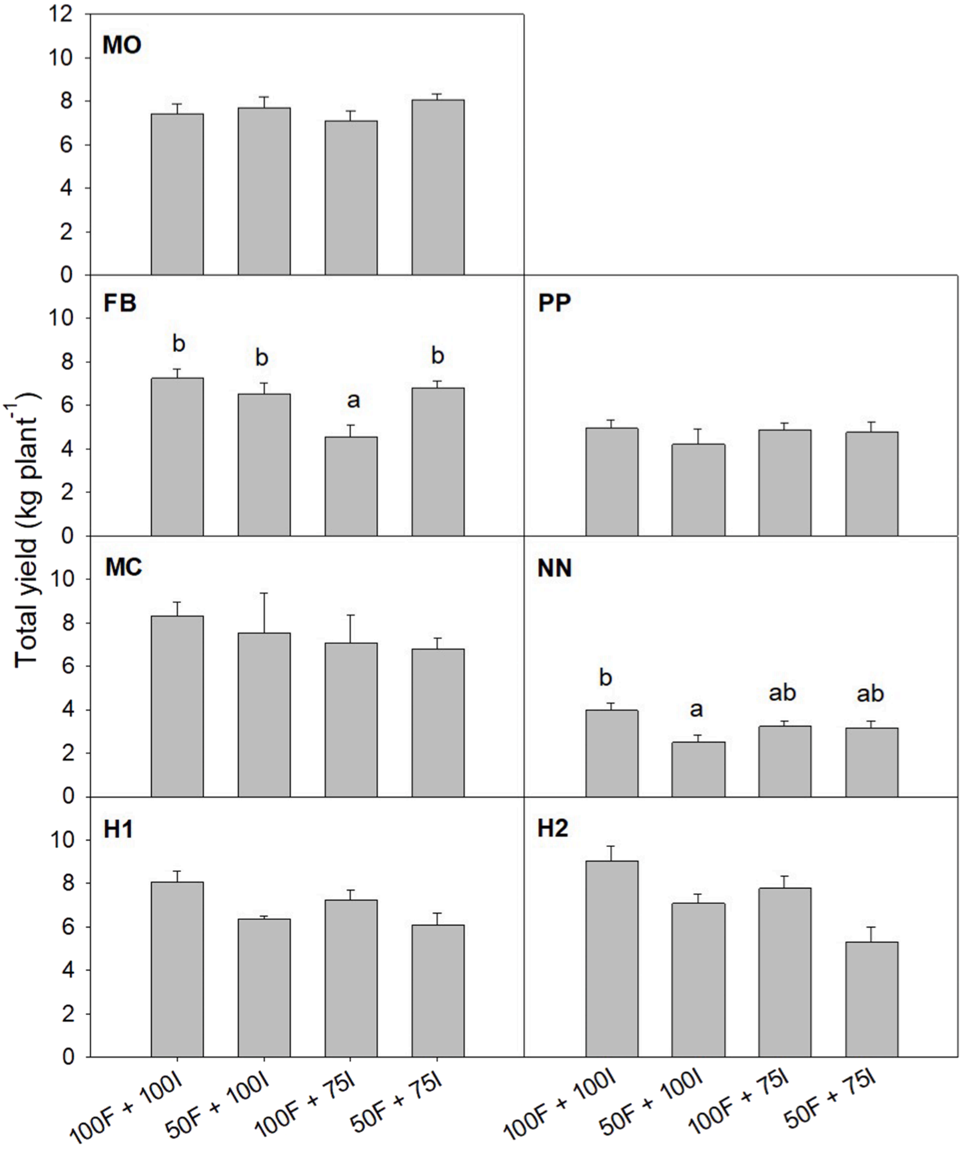

Fig. 3. Effect of the fertilisation (100 % *vs* 50 %) and irrigation (100 % *vs* 75 %) doses on yield (kg plant^{-1}) of the studied varieties (Mongo [MO], Flor de Baladre [FB], Pera Pinatar [PP], Muchamiel [MC], and Negro de Nerpio [NN]) and the experimental hybrids (H1 and H2). Different letters within each variety indicate significant differences between treatments based on the Fertilisation × Irrigation interaction, according to Duncan's test at the 5 % level. Data are means ± SE ($n = 10$).

exceptional results in the sensory analysis, likely due to other key factors influencing its sensory profile (Tieman et al., 2017).

3.2. *Effect of the treatments*

3.2.1. *Agronomic response*

After the evaluation of the impact of reduced fertilisation and irrigation on agronomic performance (measured as yield, number of fruits per plant, and mean fruit weight), PP was the only variety that did not show a significant change in response to these reductions (Table 5; Figs. 3, 4, and 5). Additionally, the total yields of MO and MC were unaffected by a reduced fertilisation or irrigation. However, MO exhibited an increase in the number of fruits and a decrease in the mean fruit weight under reduced irrigation. MC showed a similar response to

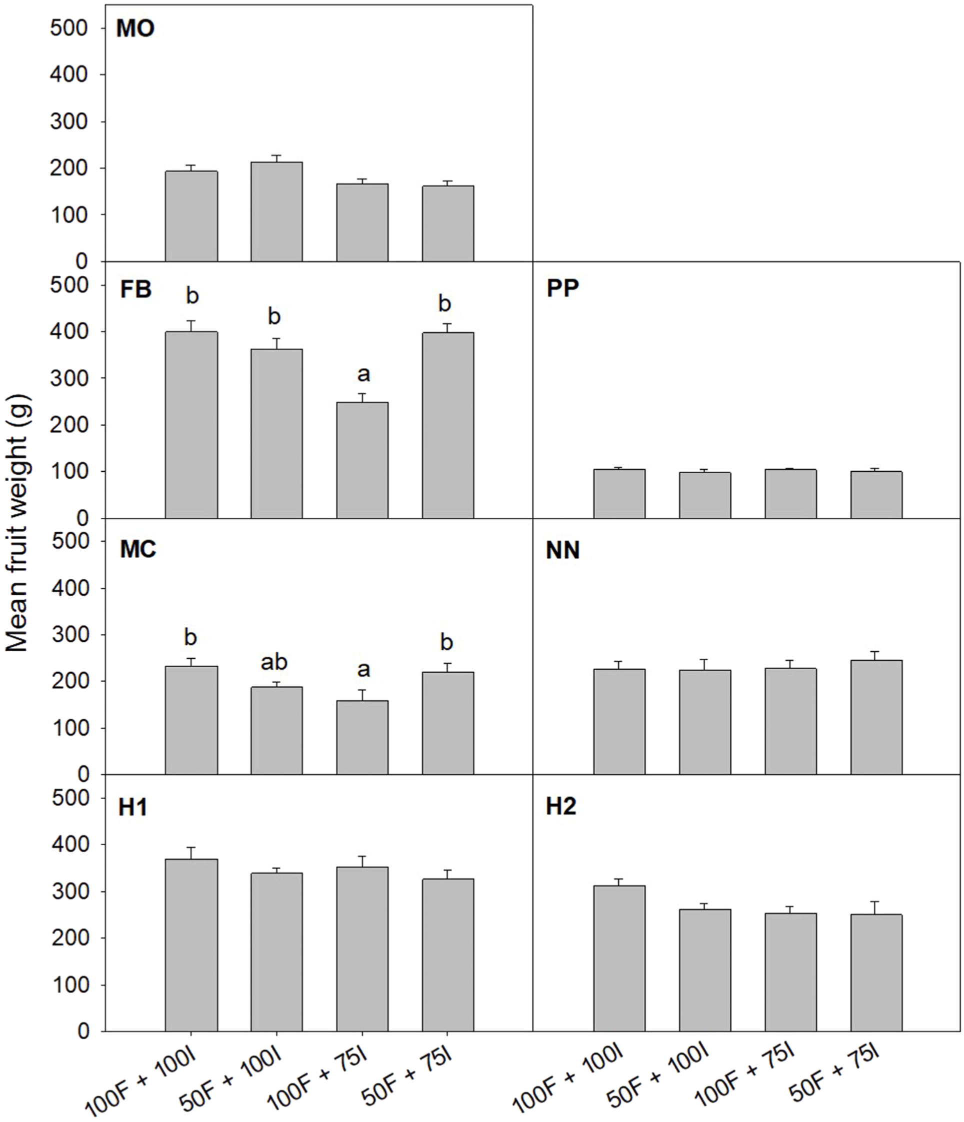

Fig. 4. Effect of the fertilisation (100 % *vs* 50 %) and irrigation (100 % *vs* 75 %) doses on mean fruit weight (g) of the studied varieties (Mongo [MO], Flor de Baladre [FB], Pera Pinatar [PP], Muchamiel [MC], and Negro de Nerpio [NN]) and the experimental hybrids (H1 and H2). Different letters within each variety indicate significant differences between treatments based on the Fertilisation × Irrigation interaction, according to Duncan's test at the 5 % level. Data are means ± SE (*n* = 10).

that found in MO, but only when fertilisation was maintained at 100 % (100F+75I). In FB, a 37 % yield decrease occurred with reduced irrigation despite maintaining fertilisation at 100 % (100F+75I), primarily due to a smaller fruit size. Conversely, NN experienced a 35 % yield reduction with decreased fertilisation and maintained irrigation (50F+100I), resulting from a lower number of fruits compared to the control. For the developed hybrids, H1 and H2, a reduced fertilisation resulted in a yield decrease, with a significant reduction in the number of fruits being observed in H2. Additionally, H2 experienced yield losses with decreased irrigation. H1 exhibited a yield reduction of approximately 20 % under both fertilisation reduction treatments (50F+100I and 50F+75I), whereas H2 showed a more pronounced 40 % decrease when both inputs were reduced (50F+75I), compared to a 20 % reduction when only fertilisation was reduced (50F+100I) and a 15 % reduction if only irrigation was reduced (100F+75I).

Previous studies suggest that low-input management has a variable effect on tomato agronomic performance that depends on the cultivar, with some cultivars showing better yield and quality under low-input conditions, and others performing better under conventional or high input systems (Meza et al., 2020; Chea et al., 2021). Among traditional varieties, PP performed consistently across all of the treatments, demonstrating adaptability to low-input conditions. This is substantiated by Carbonell et al. (2020), who observed no significant yield differences in Pera cultivars between low-input and conventional systems, suggesting the presence of efficient nutrient and water assimilation mechanisms, along with a greater stability compared to other traditional varieties, such as Muchamiel. Historically, Pera cultivars have been cultivated in marginal and subsistence farming, having been selected and developed within low-input agricultural systems over time. In contrast, varieties such as Flor de Baladre, Negro de Nerpio, and Muchamiel, widely grown in south-eastern Spain, are likely more aligned with high-input systems and modern agricultural practices (Carbonell et al., 2020). The observed impact of a reduced nutrient and irrigation supply on yield for other traditional varieties could be explained by two key factors: the sensitivity of each variety to an elevated salinity in the irrigation solution and the specific nutritional requirements of each of the cultivars. In treatment 100F+75I, reducing the irrigation water volume while maintaining the fertiliser dose led to a more saline irrigation solution, with a 25 % increase in concentration with regard to the control. Under these conditions, FB displayed yield

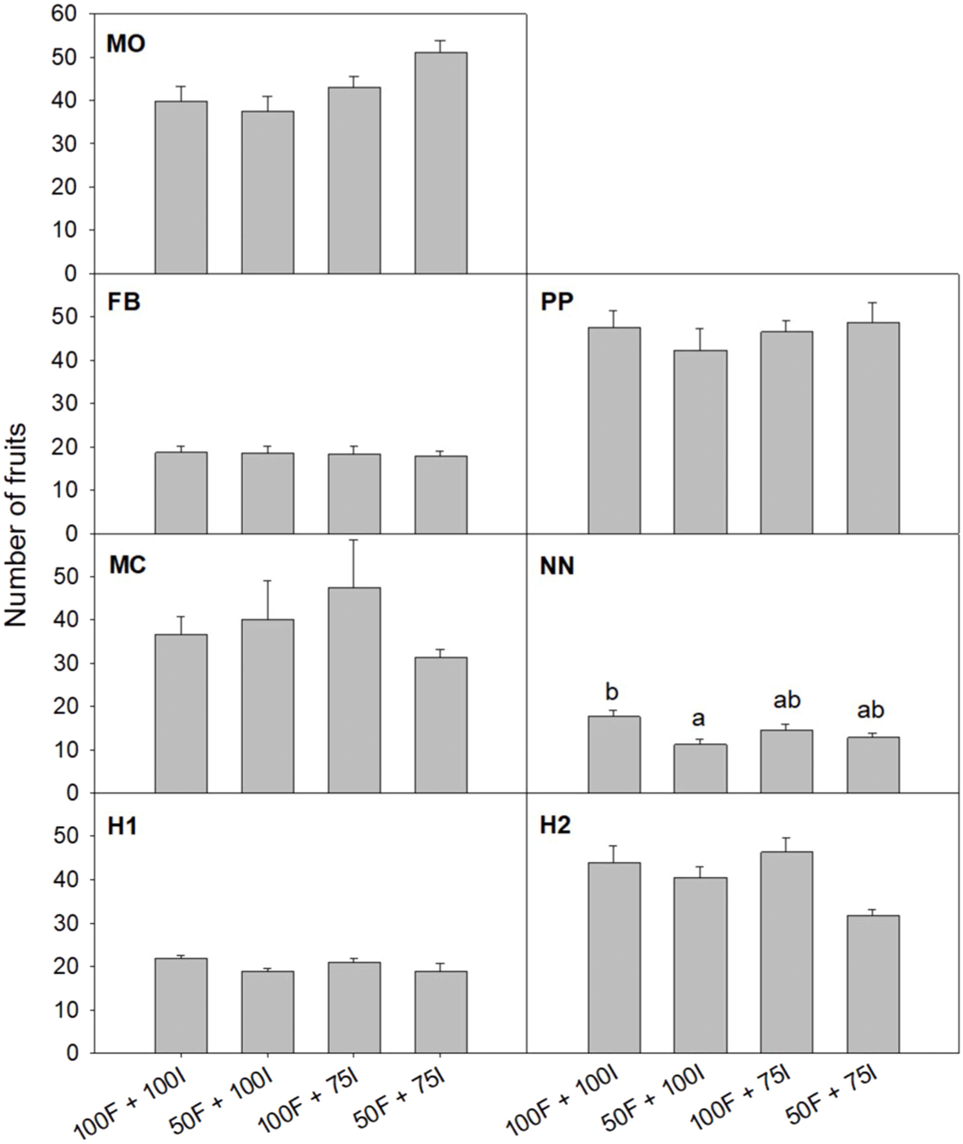

Fig. 5. Effect of the fertilisation (100 % *vs* 50 %) and irrigation (100 % *vs* 75 %) doses on the number of fruits per plant in the studied varieties (Mongo [MO], Flor de Baladre [FB], Pera Pinatar [PP], Muchamiel [MC], and Negro de Nerpio [NN]) and the experimental hybrids (H1 and H2). Different letters within each variety indicate significant differences between treatments based on the Fertilisation × Irrigation interaction, according to Duncan's test at the 5 % level. Data are means ± SE ($n = 10$).

losses, primarily due to a decrease in fruit size, probably indicating a lower tolerance to salinity despite full fertilisation. Literature suggests that saline irrigation generally reduces tomato fruit weight rather than the number of fruits, likely due to its impact on photosynthesis and the allocation of photoassimilates to the fruits (Flores et al., 2016; Meza et al., 2020). Under this treatment, MC showed an increase in the number of fruits along with a reduction in the mean fruit weight, while maintaining stable levels in overall yields. This ability to sustain yields suggests the presence of a compensatory mechanism that mitigates abiotic stress through the redistribution of photoassimilates (Osorio et al., 2014; Nogueira et al., 2022). On the other hand, a reduced fertilisation can decrease tomato yield by lowering the number of fruits rather than the fruit size, due to changes in the fruit set, but the extent of this effect depends on the requirements of the variety (Elia and Conversa, 2012; Hernández et al., 2020; Rosa-Martínez et al., 2021). The findings of the study on the effects of reduced fertilisation on the yield of NN and its derived hybrids, H1 and H2, indicated that these varieties have greater nutrient requirements than the reference and other traditional varieties. For the NN parent, yield loss due to a lower fertiliser dose was only observed in the most diluted nutrient solution treatment (50F+100I). In contrast, the yield of the hybrids decreased with any reduction in fertiliser, regardless of the irrigation rate, with H2 hybrid showing a particular sensitivity to both input reductions. This indicates that hybrid vigour is linked to a moderate to high demand for fertiliser (Carbonell et al., 2020).

3.2.2. *Fruit morphology and composition*

Concerning the morphological parameters, the shape index (SI), calculated as the ratio of longitudinal to equatorial diameters, was not influenced by the fertilisation dose in any of the varieties (Tables 6 and 7). However, a reduction in the irrigation rate decreased SI in the PP and H2 varieties. Although this decrease in SI was significant, it merely represented a reduction of approximately 6 % and did not impact the visual appearance of the PP fruits, thus likely not affecting the perception of the consumer. Firmness was unaltered by lower fertilisation rates; however, disparities were observed across certain varieties in response to a reduced irrigation. Specifically, a reduction in irrigation resulted in an increased firmness in MO, MC, and H2 varieties, as well as

Table 6
Effect of the fertilisation (100 % *vs* 50 %) and irrigation (100 % *vs* 75 %) doses on the shape index (SI), firmness (F), total soluble solids (TSS; °Brix), and acidity (g L^{-1} of citric acid) in the studied varieties (Mongo [MO], Flor de Baladre [FB], Pera Pinatar [PP], and Muchamiel [MC]).

			SI	F	TSS	Acidity
MO	*F*	*I*				
	100	*100*	0.67	1.74	5.1	3.7^{a}
	50		0.67	1.77	5.4	4.3^{ab}
	100	*75*	0.64	1.87	5.9	4.8^{b}
	50		0.66	2.17	6.0	4.4^{b}
		F	ns	ns	ns	ns
		I	ns	**	**	**
		FxI	ns	ns	ns	*
FB	*F*	*I*				
	100	*100*	0.58	1.62^{a}	5.9^{a}	4.3^{a}
	50		0.58	1.69^{a}	5.7^{a}	4.3^{a}
	100	*75*	0.57	2.52^{b}	7.1^{b}	5.0^{b}
	50		0.56	1.73^{a}	6.0^{a}	4.1^{a}
		F	ns	**	**	*
		I	ns	***	**	ns
		FxI	ns	**	*	*
PP	*F*	*I*				
	100	*100*	1.24	2.77	6.6	3.7
	50		1.25	2.98	6.1	3.6
	100	*75*	1.16	2.82	6.3	3.6
	50		1.15	2.92	6.6	3.9
		F	ns	ns	ns	ns
		I	***	ns	ns	ns
		FxI	ns	ns	ns	ns
MC	*F*	*I*				
	100	*100*	0.61	1.84	6.2^{a}	5.2^{a}
	50		0.65	1.69	5.7^{a}	4.5^{a}
	100	*75*	0.63	2.10	7.8^{b}	6.0^{b}
	50		0.63	1.89	6.6^{a}	4.8^{a}
		F	ns	ns	ns	ns
		I	ns	*	***	*
		FxI	ns	ns	*	**

*, **, *** Significant differences between means at a 5, 1 or 0.1 % level of probability, respectively; ns, non-significant at $p = 5$ %. Different letters in the same column indicate the presence of significant differences between means according to Duncan's test at the 5 % level. Data are means ($n = 6$).

Table 7
Effect of the fertilisation (100 % *vs* 50 %) and irrigation (100 % *vs* 75 %) doses on the shape index (SI), firmness (F), total soluble solids (TSS; °Brix), and acidity (g L^{-1} of citric acid) in the studied varieties (Negro de Nerpio [NN]) and the experimental hybrids (H1 and H2).

			SI	F	TSS	Acidity
NN	*F*	*I*				
	100	*100*	0.67	1.50	5.8^{a}	4.7^{b}
	50		0.65	1.51	6.5^{b}	5.2^{c}
	100	*75*	0.61	1.55	5.8^{a}	4.4^{b}
	50		0.65	1.69	5.5^{a}	4.0^{a}
		F	ns	ns	ns	ns
		I	ns	ns	**	***
		FxI	ns	ns	**	**
H1	*F*	*I*				
	100	*100*	0.59	1.67	4.6^{a}	3.7^{a}
	50		0.59	1.77	5.7^{c}	4.9^{c}
	100	*75*	0.60	1.67	5.9^{c}	5.0^{c}
	50		0.61	1.69	5.0^{b}	4.4^{b}
		F	ns	ns	ns	*
		I	ns	ns	*	*
		FxI	ns	ns	***	***
H2	*F*	*I*				
	100	*100*	0.66	1.58	5.6	4.6
	50		0.64	1.74	5.8	4.8
	100	*75*	0.61	1.79	6.2	5.1
	50		0.61	1.93	6.3	5.7
		F	ns	ns	ns	ns
		I	*	*	*	*
		FxI	ns	ns	ns	ns

*, **, *** Significant differences between means at a 5, 1 or 0.1 % level of probability, respectively; ns, non-significant at $p = 5$ %. Different letters in the same column indicate the presence of significant differences between means according to Duncan's test at the 5 % level. Data are means ($n = 6$).

in the FB variety, but only under the 100F+75I treatment. The increased firmness could enhance long-distance storage and transportation, making it a valuable trait for the introduction of traditional varieties in the market (Lázaro and Ruiz-Aceituno, 2021). However, more studies are needed to rule out that this can affect the organoleptic quality and, therefore, consumer acceptance.

Regarding fruit composition, PP was the only variety in which the treatments did not affect the concentration of total soluble solids (TSS) and acidity (Tables 6 and 7). For the remaining varieties, a reduction in irrigation levels generally resulted in increased TSS and acidity, though several fertilisation × irrigation interactions were observed depending on the variety. Reducing the irrigation rate in the MO variety increased TSS regardless of the fertilisation treatment; however, acidity only increased with reduced irrigation when full fertilisation was applied (100F+75I). Similarly, in FB and MC varieties, by reducing irrigation at full fertilisation, only an increase in TSS and acidity was observed. In the experimental hybrid H2, a significant rise in TSS and acidity was observed with a reduced irrigation, regardless of the fertilisation treatment. In H1, reducing either the fertilisers (50F+100I), the water (100F+75I), or both inputs (50F+75I) resulted in an increase in TSS and acidity compared to the control (100F+100I). Finally, in the NN variety, the treatment with the most diluted nutrient solution (50F+100I) exhibited an increase in total soluble solids (TSS) and acidity compared to the other treatments. The results of agronomic performance and fruit composition for the PP variety indicate that this variety demonstrated a greater tolerance to low-input conditions compared to the other varieties. These findings align with the observations of Carbonell et al. (2020), where a reduction in NPK did not compromise the quality of PP-type cultivars, further supporting the perception that PP is better adapted to reduced fertiliser and water inputs. The increased TSS and acidity values observed in the other varieties (MO, FB, MC, NN, H1, and H2), resulting from different fertilisation × irrigation interactions, were in most cases accompanied by yield reductions (total yield, fruit weight, and/or number of fruits), suggesting a concentration effect likely driven by an increased source/sink ratio (Hernández et al., 2020, 2022). A reduction in fruit number or size decreases overall sink demand, resulting in the allocation of assimilates from source tissues to a smaller number of sinks. This redistribution increases the assimilate load per fruit, thereby elevating metabolite concentrations on a per-fruit basis (Osorio et al., 2014).

3.2.3. *Fruit metabolites*

Understanding the impact of fertiliser and water limitations on plant yield is critical for evaluating the feasibility of low-input cultivation of traditional varieties of interest. Additionally, assessing the effects of low-input cultivation on fruit composition is necessary to determine whether such restrictions influence organoleptic and functional quality. In order to determine the viability of these varieties in low-input systems, a comprehensive analysis was performed, evaluating three low-input conditions against the control treatment: reduced fertilisation with full irrigation (50F+100I), reduced irrigation with full fertilisation (100F+75I), and simultaneous reduction of both inputs (50F+75I). The analysis focused on agronomic traits and bioactive compounds and mean values for each treatment were categorized into three response categories (neutral, positive, or negative) relative to the control, based on statistical significance determined by ANOVA tests (Table 10).

In the MO, PP, FB, and MC varieties, fertilisation without reducing the irrigation rate (50F+100I) did not affect the agronomic performance parameters, nor did it lessen the fruit concentration of the analysed metabolites related to flavour (glucose and fructose) and functional quality (vitamin C, phenolic compounds, and carotenoids) (Tables 8, 9, and 10). Moreover, under these limited fertilisation conditions, MO and

Table 8

Effect of the fertilisation (100 % *vs* 50 %) and irrigation (100 % *vs* 75 %) doses on the concentration of glucose (GLU; mg g^{-1}), fructose (FRU; mg g^{-1}), vitamin C (VC; μg g^{-1}), total phenolic compounds (TPC; μg g^{-1}), and total carotenoids (TC; μg g^{-1}) in the studied varieties (Mongo [MO], Flor de Baladre [FB], Pera Pinatar [PP], and Muchamiel [MC]).

			GLU	FRU	VC	TPC	TC
MO	*F*	*I*					
	100	*100*	13.8^{a}	17.0^{a}	138	104^{a}	62
	50		16.7^{b}	19.8^{b}	141	115^{b}	60
	100	*75*	18.1^{b}	20.2^{b}	132	115^{b}	59
	50		16.8^{b}	19.4^{b}	131	99^{a}	55
		F	ns	ns	ns	ns	ns
		I	**	*	*	ns	ns
		FxI	**	**	ns	***	ns
FB	*F*	*I*					
	100	*100*	16.6^{a}	19.8^{a}	135^{a}	104^{a}	45
	50		17.2^{a}	20.3^{a}	132^{a}	108^{a}	43
	100	*75*	20.6^{b}	23.4^{b}	156^{b}	122^{b}	53
	50		16.8^{a}	20.5^{a}	134^{a}	100^{a}	50
		F	ns	ns	*	ns	ns
		I	*	*	*	ns	**
		FxI	*	*	*	**	ns
PP	*F*	*I*					
	100	*100*	17.2	19.5	136	126	74
	50		18.1	20.2	144	130	72
	100	*75*	17.2	18.3	126	121	63
	50		20.0	21.2	145	118	72
		F	*	*	*	ns	ns
		I	ns	ns	ns	ns	ns
		FxI	ns	ns	ns	ns	ns
MC	*F*	*I*					
	100	*100*	16.2^{a}	19.2^{a}	133	117	56^{a}
	50		16.1^{a}	19.0^{a}	126	128	55^{a}
	100	*75*	18.7^{b}	21.2^{b}	145	127	63^{b}
	50		15.7^{a}	18.5^{a}	130	118	51^{a}
		F	*	*	ns	ns	ns
		I	ns	ns	ns	ns	ns
		FxI	*	*	ns	ns	**

*, **, *** Significant differences between means at a 5, 1 or 0.1 % level of probability, respectively; ns, non-significant at $p = 5$ %. Different letters in the same column indicate the presence of significant differences between means according to Duncan's test at the 5 % level. Data are means ($n = 6$).

Table 9

Effect of the fertilisation (100 % *vs* 50 %) and irrigation (100 % *vs* 75 %) doses on the concentration of glucose (GLU; mg g^{-1}), fructose (FRU; mg g^{-1}), vitamin C (VC; μg g^{-1}), total phenolic compounds (TPC; μg g^{-1}), and total carotenoids (TC; μg g^{-1}) in the studied varieties (Negro de Nerpio [NN]) and the experimental hybrids (H1 and H2).

			GLU	FRU	VC	TPC	TC
NN	*F*	*I*					
	100	*100*	14.2	17.2	109	118	93^{ab}
	50		14.6	17.3	102	107	98^{b}
	100	*75*	14.1	17.1	119	110	103^{b}
	50		15.4	17.9	124	118	83^{a}
		F	ns	ns	ns	ns	ns
		I	ns	ns	***	ns	ns
		FxI	ns	ns	ns	ns	*
H1	*F*	*I*					
	100	*100*	14.5^{a}	17.7^{a}	122^{a}	107^{a}	64
	50		17.4^{b}	19.7^{b}	137^{b}	126^{b}	61
	100	*75*	15.6^{a}	18.4^{ab}	125^{ab}	119^{b}	63
	50		15.3^{a}	18.0^{a}	118^{a}	99^{a}	59
		F	*	ns	ns	ns	ns
		I	ns	ns	*	**	ns
		FxI	*	*	*	*	ns
H2	*F*	*I*					
	100	*100*	14.8^{a}	17.2^{a}	119^{a}	105	54
	50		17.0^{b}	19.3^{b}	133^{b}	114	59
	100	*75*	18.3^{b}	19.7^{b}	132^{b}	116	52
	50		15.7^{a}	16.8^{a}	116^{a}	109	58
		F	ns	ns	ns	ns	ns
		I	ns	ns	ns	ns	ns
		FxI	**	**	**	ns	ns

*, **, *** Significant differences between means at a 5, 1 or 0.1 % level of probability, respectively; ns, non-significant at $p = 5$. Different letters in the same column indicate the presence of significant differences between means according to Duncan's test at the 5 % level. Data are means ($n = 6$).

PP fruits exhibited higher glucose and fructose levels compared to the control. Additionally, MO showed an increase in phenolic compound content, whereas PP displayed elevated vitamin C concentrations. Conversely, despite the observed increase in certain metabolites of interest under this fertilisation restriction, the NN variety and its hybrid progeny (H1 and H2) were not suitable candidates for these low-fertilisation conditions, as it had a detrimental effect on their agronomic performance. The varieties that maintained a level in all of the productivity parameters that was comparable to that found in the control under reduced irrigation, without reducing fertilisation (100F+75I), were PP, NN, and H1. Additionally, this irrigation limitation led to an increased concentration of vitamin C in NN and higher levels of fructose and phenolic compounds in H1 compared to the control. MO, FB, MC, and H2 varieties exhibited an increase in the concentration of one or more metabolites of interest under this treatment; however, this increase was accompanied by a reduction in one of the yield parameters, either total yield and/or mean fruit weight. For PP, the promising results (which demonstrate its ability to maintain or even increase certain quality-related metabolites under reduced fertilisation or irrigation without compromising yield) were also made evident when both fertilisation and irrigation were reduced (50F+75I), resulting in an increase in glucose, fructose, and vitamin C concentration under this combined treatment (Table 8). Certain varieties that responded well to the reduction in the fertiliser dose, specifically FB and MC, as well as to a reduced irrigation, such as NN, also demonstrated a resilient response to the combined reduction of both inputs in terms of agronomic and quality considerations. Furthermore, under this combined low-input treatment, an increase in the phenolic compound concentration was observed for FB, whereas NN showed an increase in vitamin C concentration.

Irrigation and fertilisation are essential agronomic practices for optimizing tomato yield and fruit quality. In general, yield and fruit quality are more sensitive to changes in irrigation management than to modifications in fertilisation practices (Wang and Xing, 2017). Although many studies have shown that limited irrigation can be an effective strategy to improve tomato fruit composition while reducing water consumption, its impact on yield and quality is complex and varies significantly depending on the tomato variety (Lu et al., 2021). Numerous studies have also explored the effects of mineral nutrient supply on tomato yield and fruit quality, but the results have been highly variable, largely owing to differences in the experimental factors, cultivars, and environmental conditions (Cheng et al., 2021; Hernández et al., 2020). The mechanisms underlying the response to reduced irrigation and fertilisation of primary and secondary metabolites in fruits remain poorly understood. Some of the key responses that were observed in this study, consistent with previous research, include the following: (i) the ability to attract photoassimilates to the fruit is defined as sink strength, which influences metabolite distribution to fruit throughout the plant. A source-sink imbalance, often resulting from yield loss due to reduced fertilisation and irrigation, can lead to higher metabolite concentrations in the fruit (Bénard et al., 2009; Flores et al., 2016; Osorio et al., 2014); (ii) osmotic adjustment is an adaptive mechanism to maintain cell turgor under water stress. To enhance osmotic tolerance to water loss, plants increase the concentration of different metabolites in the cytoplasm, especially soluble sugars, such as fructose and glucose (Hou et al., 2020; Ripoll et al., 2014); (iii) reduced fertilisation and/or irrigation may decrease vegetative growth, resulting in an increased light reception on fruit surface. Enhanced light exposure facilitates the accumulation of primary and secondary metabolites by increasing fruit photosynthesis and fruit sugar content, while also upregulating enzymes associated with secondary metabolism that are

Table 10
Comprehensive analysis of the response of the studied varieties (Mongo [MO], Flor de Baladre [FB], Pera Pinatar [PP], Muchamiel [MC], and Negro de Nerpio [NN]) and the experimental hybrids (H1 and H2) under 50F+100I, 100F+75I, and 50F+75I against the control treatment 100F+100I.

		Agronomic			Metabolites				
		Y	MFW	FN	FRU	GLU	VC	TPC	TC
50F+100I	MO				+	+		+	
	FB								
	PP				+	+	+		
	MC								
	NN	−		−					
	H1	−			+	+	+	+	
	H2	−		−	+	+	+		
100F+75I	MO		−	+	+	+	−	+	
	FB	−	−		+	+	+	+	+
	PP								
	MC		−		+	+			+
	NN						+		
	H1				+			+	
	H2	−			+	+	+		
50F+75I	MO		−	+	+	+	−		
	FB								+
	PP				+	+	+		
	MC								
	NN						+		
	H1	−							
	H2	−		−					

Mean values for each treatment and trait were classified into three response categories: neutral (yellow), positive (+ and green), and negative (− and red). Responses were determined according to ANOVA analyses and statistical significance of Tables 5, 8, and 9.

activated by light (Gautier et al., 2009; Hernández et al., 2020; Hou et al., 2020); (iv) oxidative stress occurs as a secondary response to primary stress factors, such as low fertilisation or irrigation. Reduced photosynthetic activity in leaves leads to an excessive production of reactive oxygen species (ROS), which damage cellular components and induce oxidative stress. To counteract this, plants activate biochemical strategies, including the enhanced synthesis of antioxidants such as carotenoids, vitamin C, and phenolic compounds (Ripoll et al., 2014; Egea et al., 2022). Vitamin C plays a central role in ROS detoxification, acting as an electron donor for ascorbate peroxidase (APX) in the reduction of H_2O_2 to H_2O, and also by directly regenerating tocopherol from its radical form (Mellidou et al., 2021). Additionally, the biosynthetic pathway of carotenoids and phenolic compounds appears to be under ROS/redox control, and their accumulation is frequently induced under abiotic stress conditions as part of the plant's adaptive response (Ripoll et al., 2014). Thus, the observed response of traditional germplasm to limited irrigation and fertilisation could be explained by a combination of various physiological and biochemical mechanisms. These mechanisms can differ significantly between varieties, influencing their growth and yield, as well as the synthesis and accumulation of metabolites that are linked to fruit quality, to different extents. The variable response makes these traditional varieties a valuable resource in the search for a germplasm that is suitable for low-irrigation and/or low-fertilisation conditions, or for enhancing organoleptic and nutritional quality without compromising the agronomic performance. The findings provide a framework for future research, with a particular focus on enhancing stress resilience through approaches such as grafting and plant-microbial interactions, which have been shown to improve plant responses to abiotic stress (Gisbert-Mullor et al., 2020; Yuan et al., 2024).

In summary, from the evaluation of the response to low-input cultivation of the studied varieties, which were previously selected for having a productivity that is comparable to that found in the commercial varieties and their outstanding quality, several conclusions can be inferred. PP variety exhibited the most favourable cost–benefit balance under reduced input conditions, as maintained yield while significantly increasing the concentration of primary (glucose and fructose) and secondary (vitamin C) metabolites. In contrast, hybrid H2 showed the least favourable response, as limitations in fertilisation, irrigation, or both led to yield reductions without consistently increasing the concentration of metabolites in the fruit. The yield and quality of FB and MC fruits were also maintained under low fertilisation, either alone or in combination with low irrigation. Notably, FB showed an increase in the phenolic compound concentration under the latter treatment, highlighting its potential for enhanced nutritional value in response to low-input cultivation. Finally, the H1 hybrid demonstrated an improved productivity compared to its parental variety NN, and exhibited a strong tolerance to low irrigation conditions. It maintained a yield that was similar to that observed under control conditions, and showed an enhanced quality, particularly in terms of increased fructose concentration and phenolic compound content. These findings have significant implications for their integration into current agricultural systems: farmers could adopt these varieties to reduce input dependency, lower production costs, and increase crop value because of their outstanding quality. Alternatively, future breeding programmes can build on these varieties to address new objectives, such as enhancing tolerance to abiotic and biotic stresses.

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CRediT authorship contribution statement

Alicia Sánchez: Writing – review & editing, Writing – original draft, Visualization, Software, Methodology, Investigation, Formal analysis, Data curation. **Virginia Hernández:** Visualization, Validation, Investigation, Formal analysis. **Pilar Hellín:** Validation, Resources, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Elia Molina:** Methodology. **José Fenoll:** Visualization. **Pilar Flores:** Writing – review & editing, Writing –

original draft, Visualization, Validation, Software, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.scienta.2025.114307.

Data availability

The data that has been used is confidential.

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