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Original Research Paper

Variegated bioactive potential and different productive responses displayed by a set of polychromatic mini plum tomato cultivars

Claudio Cannata*, Federico Basile, Rosario Paolo Mauro, Maria Giordano, Melissa Carmen Susino and Cherubino Leonardi

Dipartimento di Agricoltura, Alimentazione e Ambiente (Di3A), University of Catania, Via Valdisavoia, 5-95123 Catania, Italy
federico.basile@phd.unict.it; rosario.mauro@unict.it; maria.giordano@unict.it; melissa.susino@studium.unict.it; cherubino.leonardi@unict.it
* Corresponding author: claudio.cannata@phd.unict.it

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Abstract: This study aimed to evaluate, from a bio-agronomical and qualitative perspective, 15 greenhouse mini plum tomato cultivars differing for epicarp colour (yellow, orange, red and brownish), and recently introduced in South-Eastern Sicily. 'Santy Yellow' (yellow fruit), 'Santy Naranja' and 'Bamano' (both with orange fruit) proved the highest marketable yield (3.24 kg plant^{-1}, on average), whereas fruit weight, shape index, firmness and dry matter content peaked in 'Top Zohar' (brownish fruit), 'Dolly', 'Santy Yellow' (both with yellow fruit) and 'Santy Naranja' (orange), respectively. Moreover, 'Blondy' and '605156' (both yellow-fruited) showed the highest total soluble solids (10.2 °Brix) and titratable acidity (4.42 g CAE L^{-1}), respectively. From a functional viewpoint, the brownish-fruited cultivars had the highest contents of total phenols and chlorophylls (3237 mg GAE kg^{-1} DW and 157 mg kg^{-1} DW, respectively), especially in the case of 'Thaiti' (3571 mg GAE kg^{-1} DW) and 'Dolcenera' (201.7 mg kg^{-1} DW). Differently, the red-fruited cultivars showed the highest contents of total carotenoids (354 mg kg^{-1} dry weight), and lycopene (235 mg kg^{-1} DW), whereas the yellow-fruited ones displayed the lowest carotenoids accumulation, particularly in 'Ivorino' (33 mg kg^{-1} dry weight). The present study provides useful information about the adaptability of these cultivars to the greenhouse conditions thereby assisting the horticultural sector to fulfill the increasing market demands for a diversified product from a qualitative and functional viewpoint.

Keywords: *Solanum lycopersicum* L.; marketable yield; fruit quality; total phenols; antioxidant activity; total carotenoids.

1. Introduction

Tomato (*Solanum lycopersicum* L.) is one of the most cultivated and consumed vegetable in the world, with a high economic value and nutritional potential (Mauro et al., 2015; Jian et al., 2023). Each year, almost five million hectares of land are globally devoted to tomato cultivation (Alenazi and Khandaker, 2021). Its widely recognized acceptability among consumers is related to the multi versatility as food and its healthy characteristics. Tomato is rich in polyphenols, carotenoids, minerals, vitamins, minerals, and other antioxidant (Navarro-González, García-Alonso and Periago, 2018; Vats et al., 2020). Several tomato visual characteristics contribute to the overall tomato fruit quality perceived by consumers. Among these, epicarp colour, shape, and fruits size guide consumers' purchasing behavior (Thakur et al., 1996; Bertin and Génard, 2018; Gonzali and Perata, 2021).

The importance of tomato for the market and human health has led to an increasing interest for the study of genetic functionality and nutrients metabolism. Unlike the past when tomato breeding programs used to be focused primarily on maximizing yield, shelf-life, and disease resistance, nowadays the emphasis has shifted towards enhancing the overall quality and nutritional value of the fruit, to meet the dietary and long-term health challenges posed by the increasing consumers' demand for high-quality, nutrient-dense vegetables (Ilahy et al., 2018; Mauro, et al., 2020; Buturi et al., 2021). The continuous introduction of novel cultivars on the market made tomato one of the most dynamic crops among vegetables (Liu et al., 2021; Sun et al., 2020). For certain tomato typologies, such as mini plum tomatoes for fresh consumption, this phenomenon is particularly relevant, as new cultivars with different fruits pigmentation are frequently introduced for cultivation, resulting in a broad commercial diversification of the product. Many pre-harvest factors, such as the choise of cultivar, agricultural practices, growth conditions and ripening stage, and their interaction, can affect tomato quality. As an example, the adaptability of the genotype to the growth environment is especially important, as it can impact the tomato quality attributes and its potential health benefits (Dorais et al., 2008; Choi et al., 2014; Bertin and Génard, 2018).

Given the economic and nutritional importance of tomato, it is crucial to carefully evaluate the novel cultivars to assess their potential benefits and limitations, including their yield and functional characteristics. Thus, this study aimed to examine 15 mini plum tomato cultivars recently introduced in Southern Italy. These cultivars are categorized based on their fruit pigmentation (red, yellow, orange, brownish) and evaluated from a bio-agronomic, qualitative and bio-chemical standpoint. For this purpose, total and marketable yield, fresh and dry fruit weight, some extrinsic characteristics (shape and firmness) as well as nutritional and bioactive components (total soluble solids, total phenols, total carotenoids, chlorophylls, and lycopene content), were evaluated.

2. Materials and Methods

2.1. Experimental site, plant material, and crop management

A greenhouse experiment was conducted in 2022 (from February 14th to July 15th) in Pachino (South of Siracusa, Sicily; 36°73' N, 15°06' E, 60 m a.s.l.), in a highly representative area for greenhouse tomato cultivation in Southern Italy. The local climate is semi-arid Mediterranean, with mild winters and warm, rainless summers. The trial was conducted in the center of an East-West oriented, multi-span cold greenhouse (100 × 50 m) having a steel tubular structure, lateral windows along the sides, and covered with an ethylene vinyl acetate film (200 µm-thick, total visible transmission > 84%). The soil hosting the experiment, which had been planted with tomatoes for the last 10 years, at the beginning of the trial had the characteristics reported in Table 1.

Fifteen recently introduced mini plum cultivars were chosen owing to their different epicarp colour (Table 2). On February 14th, four-week-old tomato seedlings (with 3 true-leaves), selected for uniformity and health appearance, were transplanted in North-South oriented rows (0.30 × 2.00 m, corresponding to a planting density of 1.67 plants m^{-2}) and trained to two stems up to the eighth cluster. Each experimental unit included 18 plants (3 rows each including 6 plants, net of borders). Drip irrigation (two emitters per plant, each working at 0.1 MPa with a flow rate of 1.2 L h^{-1}) was performed up to field capacity when the external accumulated evapotranspiration (calculated through the Penman-Monteith equation) reached 40 mm. Concerning fertigation, the following amounts of nutrients were supplied throughout the cycle (expressed as kg ha^{-1}): 229 N, 216 P_2O_5, 339 KO_2, 255 MgO, 119 Ca, 288 SO_3, 7.50 Fe, 0.3 Mn, 0.055 Zn, 0.018 Mo and 0.0065 B. Bumblebees were used to allow pollination, whereas pest management was performed as per local custom. Further crop practices included manual removal of lateral stems. Fruit harvests were carried out by hand from 25 May to 15 July.

2.2. Yield and related components

Immediately after each harvest, fruit yield was determined gravimetrically and divided in total, unmarketable (fruits with shape/colour/integrity defects) and marketable (fruits without defects).

Table 1. Soil characteristics at the experiment site (0-40 cm depth).

Soil characteristics	Units	Value
Clay	%	26.0
Silt	%	31.4
Sand	%	42.6
Organic matter	%	0.53
pH	-	7.73
Cation exchange capacity	cmol kg^{-1}	21.0
Total N	mg kg^{-1}	1.40
Available P_2O_5	mg kg^{-1}	13.7
Exchangeable K	mg kg^{-1}	78.0
Exchangeable Mg	mg kg^{-1}	300
Exchangeable Ca	mg kg^{-1}	3400
Exchangeable Na	mg kg^{-1}	200

Table 2. Main information related to the studied cultivars.

Cultivar	Fruit colour	Seed company
'Angelle'	Red	Syngenta Italia, Milano (MI), Italy
'Fanello'	Red	TSI Italia srl, Foggia (FG), Italy
'605156'	Yellow	Syngenta Italia, Milano (MI), Italy
'Dolly'	Yellow	ISI Sementi S.p.A, Parma (PR)
'Ivorino'	Yellow	Syngenta Italia, Milano (MI), Italy
'Santy Yellow'	Yellow	Enza Zaden Italia srl, Viterbo (VT), Italy
'Bamano'	Orange	Syngenta Italia, Milano (MI), Italy
'Blondy'	Orange	ISI Sementi S.p.A, Parma (PR)
'Santy Naranja'	Orange	Enza Zaden Italia srl, Viterbo (VT), Italy
'Yuka'	Orange	TSI Italia srl, Foggia (FG), Italy
'Black Pearl'	Brownish	ISI Sementi S.p.A, Parma (PR)
'Dolcenera'	Brownish	TSI Italia srl, Foggia (FG), Italy
'Melange'	Brownish	ISI Sementi S.p.A, Parma (PR)
'Thaiti'	Brownish	Syngenta Italia, Milano (MI), Italy
'Top Zohar'	Brownish	TSI Italia srl, Foggia (FG), Italy

2.3. Carpometric traits

The fruits ripened between June 6th and 15th (i.e., those belonging to the 3rd cluster) were chosen for an in-depth characterization. Within 3 hours from harvest, these fruits were transported to the laboratory and processed. Fruits longitudinal (L) and transversal (D) diameters were measured with a digital calliper (CDJB15, Borletti), and their ratio was used to describe the fruit shape index (L/D). Fruit firmness was measured with a texture analyser (Stable Micro Systems model TA-XT2), expressing the force (g) needed to induce a 2 mm deformation of the fruits along their transversal axis among two steel plates. Twenty fruits per replicate, selected for uniform size and colour within each cultivar, were flash frozen and lyophilized in a freeze-dryer (mod. Alpha 1–4 LD plus, Martin Christ, Osterode am Harz, Germany) until constant weight to determine gravimetrically their dry matter content (DM%). Twenty representative fruits per replicate were homogenized and immediately analysed for total soluble solids (TSS) and titratable acidity (TA). Total soluble solids (°Brix) were determined with a digital refractometer DBX-55°

(Atago Co., Ltd., Tokyo, Japan) provided with an automatic temperature compensation system. Titratable acidity was determined by neutralization of the free acids with a titration solution of NaOH (0.1 M) up to the changing colour of phenolphthalein; results were expressed as g of citric acid equivalent (CAE) L^{-1}.

2.4. Fruit chromatic coordinates

The fruit chromatic coordinates (CIEL*a*b*) were measured along the equatorial axis of eight fruits per replicate (16 readings per plot). The tristimulus Chroma Meter (CR-200, Konica Minolta, Inc., Tokyo, Japan) used was previously calibrated with a UE-certified standard white tile. Lightness (L*), green–red (a*), and blue-yellow (b*) values were measured with illuminant D65/10° and used to calculate Hue angle and Chroma, according to the standard equations (McGuire, 1992).

2.5. Biochemical variables

For the biochemical analyses, freeze-dried samples previously stored at -80 °C, were ground using a mill (A11 basic, IKA, Staufen, Germany). All further analyses were performed using a UV-Vis spectrophotometer (mod. UV-1601, Shimadzu Corporation, Kyoto, Japan).

2.5.1. Total phenolic content

Total phenolic content (TPC) of tomato fruits was determined using the Folin-Ciocâlteu method as described by Cicco et al. (2009), with minor modifications. Briefly, 0.05 g of lyophilized powder per sample were mixed with 1 mL of 80% methanol in centrifuge tubes. The extraction was carried out using a thermal bath at 70 °C for 1 hour. After that, tubes were centrifuged for 5 minutes at 5 °C and 4500 rpm. An aliquot of the extract (0.1 mL) solutions was mixed with 0.1 mL Folin-Ciocâlteu reagent (10% v/v) and allowed to react at room temperature for 2 minutes. Then, 0.8 mL of sodium carbonate (6% w/v) were added, and tubes were incubated at 40 °C for 20 minutes. The absorbance of samples was read at 760 nm. Gallic acid was used as standard to calculate a calibration curve obtained by plotting the absorbance of different standard solutions against their known contents of gallic acid ($r^2 = 0.999$, p-value < 0.001). TPC values were reported as mg gallic acid equivalents (GAE) kg^{-1} dry weight (DW).

2.5.2. Chlorophylls, total carotenoids, and lycopene content

Chlorophyll (Chl) *a* and *b* content and total carotenoids were determined according to Lichtenthaler and Buschmann (2001). Briefly, 0.05 g of lyophilized samples were added to 5 mL acetone. The extraction was aided using an ultrasonic bath for 10 minutes, then the samples were centrifugated for 10 minutes at 6 °C and 4500 rpm. The absorbance (Abs) of the supernatant was measured at 470, 644.8, and 661.6 nm (hereafter Abs_{470}, $Abs_{644.8}$, and $Abs_{661.6}$, respectively) and the obtained values were used to calculate Chl *a*, Chl *b*, and total carotenoids contents using the following equations:

$$\text{Chl } a = 11.20 \times Abs_{661.6} - 2.04 \times Abs_{644.8} \quad \text{(eq. 1)}$$

$$\text{Chl } b = 20.13 \times Abs_{644.8} - 4.19 \times Abs_{661.6} \quad \text{(eq.2)}$$

$$\text{Total carotenoids} = (1000 \times Abs_{470} - 1.82 \times \text{Chl } a - 85.02 \times \text{Chl } b)/198 \quad \text{(eq. 3)}$$

The results were expressed as mg kg^{-1} DW.

Lycopene content was determined according to Anthon and Barrett (2007) with minor modifications. Briefly, 0.05 g of lyophilized sample were mixed in a glass tube with 10 mL of extracting solution containing hexane, acetone, and ethanol in a proportion of 2:1:1 (v:v:v), plus 0.05% w/v butylated hydroxytoluene. The extraction was initially aided using an ultrasonic bath for 5 minutes, then samples were kept in ice and the extractions were carried out in dark on an orbital shaker (IKA KS 501 Digital, Staufen, Germany) at 180 rpm for 30 minutes. After the extraction, 3 mL of deionized water were added to each glass tube and samples were shaken for further 5 minutes. Afterward, to allow the phase separation, the glass tubes were left at room temperature for 5 minutes and centrifugated for further 5 minutes at 2000 rpm (5 °C). The absorbance of the hexane layer was measured spectrophotometrically in a 1 cm path length quartz cuvette at 444 and 503 nm using hexane as blank. Lycopene content was calculated using the following equation (Anthon and Barrett, 2007):

$$\text{Lycopene} = (6.95 \times Abs_{503} - 1.59 \times Abs_{444}) \times 0.55 \times 537 \times (V/W) \qquad \text{(eq. 4)}$$

where Abs_{444} is the absorbance at 444 nm, Abs_{503} is the absorbance at 503 nm, 0.55 is the ratio of the final hexane layer volume to the volume of extracting solution added, V is the volume of extracting solution added (ml), 537 (g mol^{-1}) is the molecular weights of lycopene, and W is the weight of tomato sample analysed (mg). Results were reported as mg kg^{-1} DW.

2.5.3. Antioxidant Activity: DPPH and FRAP assays

The antioxidant activity of the fruit extracts was determined using the 2-diphenyl-1-picrylhy-drazyl (DPPH) assay and the ferric reducing antioxidant power (FRAP) assay. The DPPH assay was carried out as described by Brand-Williams et al. (1995) and Buturi et al. (2023), with minor modifications. Briefly, 0.1 g of lyophilized sample was mixed with 1.5 mL methanol solution (80%), macerated at 70 °C for 15 minutes, and then centrifuged for 5 minutes at 10000 rpm (5 °C). Then, 0.010 mL of supernatant was added to 0.99 mL of a daily prepared DPPH solution (3.12×10^{-5} M), vortexed, and incubated in the dark at room temperature for 30 minutes; a blank was prepared with only 1 mL of DPPH solution. The decrease in absorbance at 517 nm was measured spectrophotometrically after 30 minutes the reaction was started (at room temperature and in the dark). Results were reported as percentage of inhibition (% In.) of DPPH calculated as follow:

$$\text{DPPH (\% In.)} = [(Abs\ C_0 - Abs\ S)/Abs\ C_0)] \times 100 \qquad \text{(eq. 5)}$$

where Abs C_0 is the absorbance of the blank at time 0 (before incubation), and Abs S is the absorbance of the sample after the incubation.

The FRAP assay was adapted from Benzie and Strain (1999) according to Buturi et al. (2022). Briefly, 0.05 g of lyophilized sample were mixed with 10 mL methanol 100%, vortexed, and centrifugated for 10 minutes at 4500 rpm. Next, 0.150 mL of supernatant were mixed with 0.3 mL ultrapure water. The solution obtained was mixed with 3 mL FRAP reagent, recently prepared. Finally, after 10 minutes of reaction, the absorbance was measured at 593 nm. The FRAP values were calculated from a standard curve obtained using different solutions with known concentrations of Trolox (±)-6-Hydroxy-2,5,7,8-tetra-methylchromane-2-carboxylic acid) ($r^2 = 0.999$ p-value < 0.001), and the results were reported as mg of Trolox equivalent (TE) kg^{-1} DW.

2.6. Statistical analyses

The experiment was arranged in a randomized blocks design with 3 replicates. All data were subject to Shapiro-Wilk's and Levene's test, to check for normal distribution and homoscedasticity, respectively. A one-way analysis of variance (ANOVA) was performed, according to the experimental design adopted in the greenhouse, and considering the cultivar as fixed effect. For the fruit chromatic coordinates, a one-way ANOVA was carried out within each colour group (red, yellow, orange, brownish). For the biochemical fruit traits, two separate ANOVAs were performed, considering either the colour class or the genotype as fixed factor. Percentage data were Bliss' transformed before the ANOVA (untransformed data are reported and discussed). Multiple mean comparisons were performed through Tukey's honestly significant difference (HSD) test ($P \leq 0.05$). All calculations were performed using Excel version 2016 (Microsoft Corporation, Redmond, WA, USA) and Excel VBA add-in DSAASTAT (Onofri, 2007).

3. Results

3.1. Yield and related components

The total yield, averaged over all cultivars, was 3.26 kg plant^{-1}, showing the highest value in 'Santy Yellow' and 'Bamano' (4.14 kg plant^{-1}, on average) and the lowest one in 'Thaiti' (2.18 kg plant^{-1}) (Figure 1A). The incidence of unmarketable yield (17.4% on average) was highly variable among the cultivars, with values ranging from 24.5 ('Bamano') to 12.7% (average values of 'Blondy', 'Ivorino', and 'Dolly') (Figure 1B). Marketable yield (2.69 kg plant^{-1}, on average) peaked in 'Santy Yellow', 'Santy Naranja', 'Bamano' and 'Yuka' (3.20 kg plant^{-1}, on average), while 'Thaiti' had the lowest value (1.82 kg plant^{-1}) (Figure 1C).

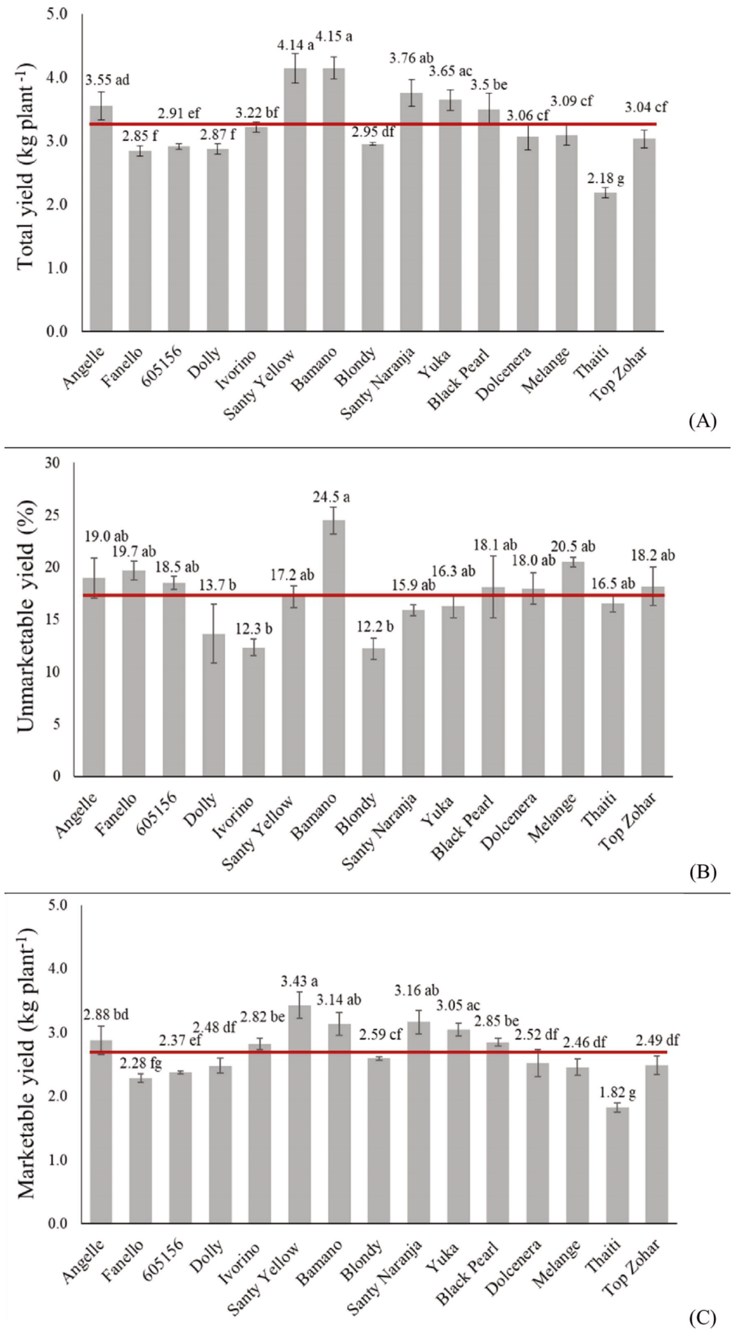

Figure 1. Total yield (A), unmarketable yield (B), and marketable yield (C) of the studied cultivars (mean ± standard error). Different letters indicate significant differences between cultivars according to the Turkey's HSD test ($p \leq 0.05$). The horizontal red line represents the overall mean.

3.2. Carpometric traits

These traits proved different variabilities among cultivars, with fruit FW and DM having the extreme $CV_{\%}$ values (25.3 and 7.82%, respectively) (Table 3). The former trait showed the lowest values in 'Angelle', 'Bamano', and 'Ivorino' (11.0 g on average), and the highest values in 'Top Zohar' and 'Black Pearl' (22.9 g on average). 'Dolcenera' and 'Melange' were the cultivars with an intermediate fruit FW (19.0 g on average) (Table 3).

Regarding the fruit shape, the L/D index attained the least values in 'Black Pearl', 'Melange', and 'Thaiti' (1.23 on average) and the highest ones in 'Dolly' and 'Ivorino' (1.63 on average), with the other cultivars having intermediate values (Table 3).

Three cultivars, namely 'Santy Yellow', 'Melange' and 'Top Zohar', stood out in terms of fruit firmness (whose values ranged between 607 and 659 g), whereas the softest fruits were measured in 'Dolly', 'Ivorino' and 'Santy Naranja' (406 g on average) (Table 3).

Despite its lower variability, fruit DM was higher in three cultivars, namely 'Angelle', 'Santy Naranja' and 'Thaiti' (12.1%, on average) whereas the lowest values were recorded in 'Santy Yellow' and 'Bamano' (9.54%, on average) (Table 3). The average value of TSS was 8.5 °Brix, and ranged between 7.01 and 10.20 °Brix, in 'Yuka' and 'Blondy', respectively (Table 3). On the other hand, TA varied between 2.90 (averaged over 'Dolly', 'Santy Yellow', 'Santy Naranja' and 'Yuka') and 4.33 g CAE L^{-1} (on the average of 'Angelle', '605156', and 'Melange') (Table 3).

Table 3. Carpometric traits of the studied tomato cultivars (mean ± standard error). Different letters within each column indicate significant differences between cultivars according to the Turkey's HSD test ($P \leq 0.05$). NS: not significant; **, ***: significant at $P \leq 0.01$ and 0.001, respectively.

Cultivar	Fruit FW (g)	L/D	Fruit firmness	Fruit DM (%)	TSS (°Brix)	TA (g CAE L^{-1})
'Angelle'	10.7±0.5 f	1.47±0.04 ab	461±11 ef	11.9±0.1 ab	8.86±0.3 bd	4.41±0.10 a
'Fanello'	14.2±0.7 de	1.44±0.06 bc	524±10 de	10.6±0.2 ac	8.02±0.2 de	3.42±0.20 bd
'605156'	14.4±0.1 d	1.43±0.03 bd	463±18 ef	10.2±0.3 bc	7.71±0.1 de	4.42±0.18 a
'Dolly'	14.7±0.3 d	1.63±0.06 a	433±23 fg	11.6±0.1 ab	9.57±0.2 ab	2.95±0.07 d
'Ivorino'	11.6±0.4 f	1.63±0.02 a	360±16 g	10.5±0.2 ac	8.73±0.2 bd	3.41±0.25 bd
'SantyYellow'	15.5±0.3 d	1.38±0.02 bd	659±21 a	9.56±0.3 c	7.85±0.2 de	2.91±0.11 d
'Bamano'	10.7±0.4 f	1.49±0.02 ab	519±18 de	9.51±0.1 c	9.20±0.3 ac	3.30±0.33 bd
'Blondy'	15.5±0.4 d	1.37±0.02 bd	535±16 ce	11.5±0.2 ab	10.2±0.20 a	3.19±0.08 bd
'Santy Naranja'	15.8±0.4 d	1.44±0.01 bc	425±12 fg	12.3±1.0 a	7.70±0.1 de	2.98±0.13 d
'Yuka'	14.6±0.3 d	1.46±0.04 ab	513±17 de	10.8±0.7 ac	7.01±0.2 e	2.75±0.05 d
'Black Pearl'	21.7±0.7 ab	1.26±0.05 de	534±20 ce	10.9±0.5 ac	8.66±0.1 bd	3.17±0.19 cd
'Dolcenera'	18.3±0.6 c	1.49±0.03 ab	552±24 bd	11.7±0.4 ab	8.58±0.3 bd	3.80±0.12 ac
'Melange'	19.6±0.6 bc	1.16±0.01 e	607±7 ac	11.1±0.4 ac	8.24±0.4 cd	4.17±0.15 a
'Thaiti'	11.9±0.7 ef	1.26±0.01 de	485±11 df	12.1±0.2 ab	9.34±0.4 ac	3.90±0.20 ab
'Top Zohar'	24.1±0.4 a	1.28±0.02 ce	619±14 ab	10.8±0.6 ac	7.89±0.1 de	3.40±0.13 bd
Mean	15.5±0.6	1.41±0.02	513±12	11±0.2	8.5±0.1	3.48±0.09
$CV_{\%}$	25.3	9.33	15.4	7.82	9.89	15.6
F-test	71.5***	15.5***	26.8***	5.21**	14.2***	15.2***

3.3. Fruit chromatic coordinates

The fruit chromatic variables of the studied cultivars are reported in Figure 2. The red cultivars showed no significant chromatic differences among them, whereas among the yellow cultivars, ‘605156’ and ‘Ivorino’ had the highest values for *L** and hue angle (on average 52.5 and 104, respectively) and the lowest a* (-6.4, on average) (Figures 2A and 2B). Among the orange cultivars, ‘Santy Naranja’ and ‘Yuka’ displayed lower L* and b* values (43.8 and 40.0, on average, respectively), compared to ‘Bamano’ and ‘Blondy’ (49.5 and 38.2, on average, respectively) (Figures 2A and 2C). A significant difference was also observed between ‘Santy Naranja’ and ‘Bamano’ in terms of Chroma, with the former cultivar displaying a significantly lower value (32.3 vs 40.4) (Figure 2E). Within the brownish cultivars, the strongest differences were observed between ‘Dolcenera’ and ‘Thaiti’, which differed mainly in terms of a* (2.55 and 10.8, respectively), Hue angle (81.5 and 59.9) and Chroma (18.5 and 21.5) (Figures 2B, 2D, and 2E).

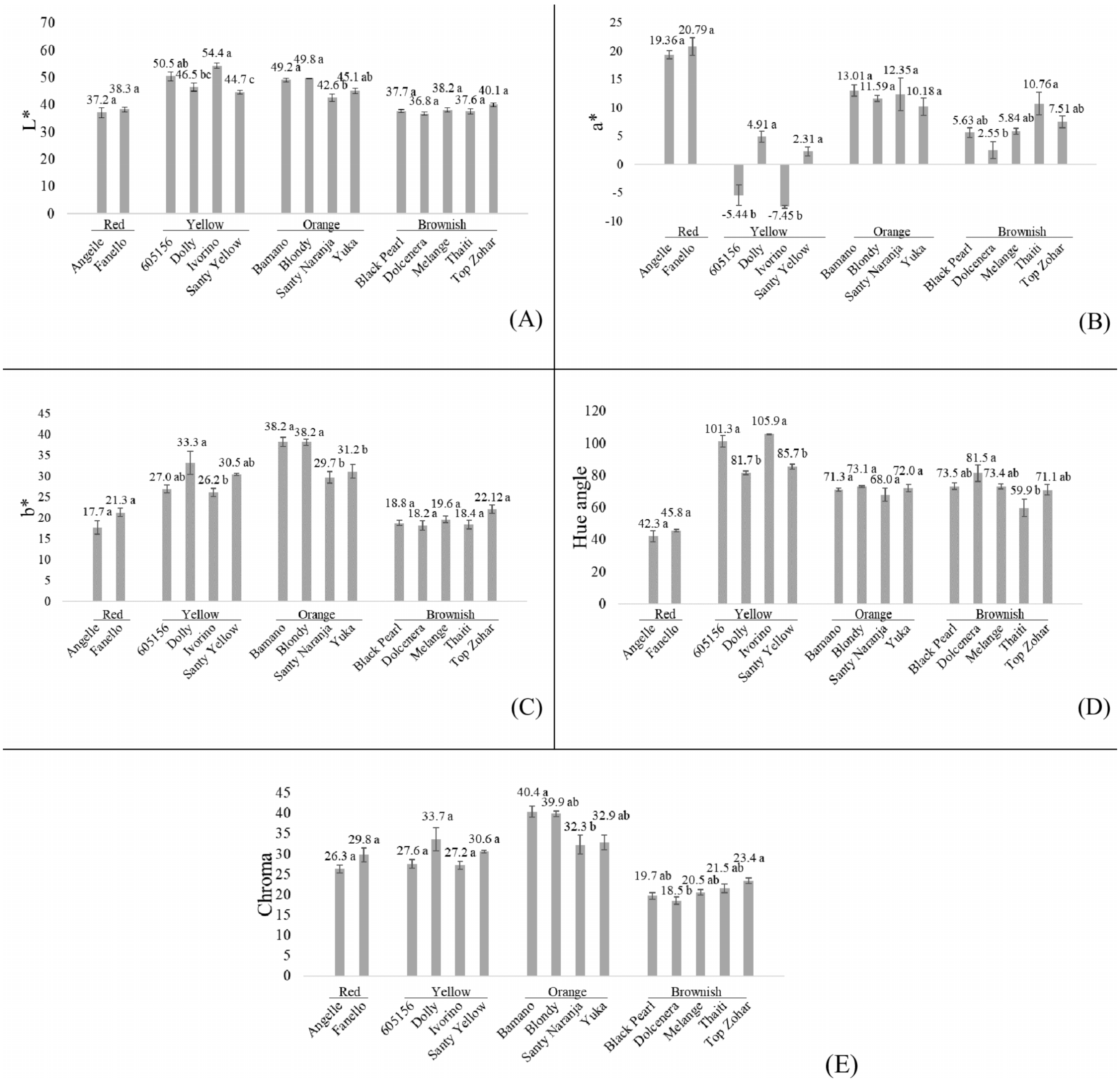

Figure 2. L* (A) a* (B) b* (C) Hue angle (D) and Croma (E) related to the studied cultivars (mean ± standard error). Within the same colour group, different letters among histograms indicate significance at Turkey’s HSD test ($p \leq 0.05$).

3.3.1. Total phenolic content

The TPC peaked in the brownish-fruited cultivars (3237 mg GAE kg^{-1} DW on average), followed by the red and yellow ones (3120 and 2997 mg GAE kg^{-1} DW on average, respectively), whereas the cultivars with orange fruits were the poorest (2763 mg GAE kg^{-1} DW on average) (Figure 3A). Accordingly, the highest TPC was measured in 'Thaiti' and 'Top Zohar' (3488 mg GAE kg^{-1} DW, on average), whereas 'Bamano' and 'Blondy' showed the least values (2520 mg GAE kg^{-1} DW, on average) (Table 4).

3.3.2. Chlorophyll *a* and *b*, total carotenoids, and lycopene content

The brownish cultivars stood out in terms of Chl *a* + *b* content (157 mg kg^{-1} DW), whereas the other colour classes displayed considerably lower values, with no significant differences among them (Figure 3B). Accordingly, 'Angelle', 'Fanello' (red fruits), '605156' 'Dolly', 'Ivorino', 'Santy Yellow' (yellow fruits) along with 'Bamano', 'Blondy', 'Santy Naranja', and 'Yuka' (orange fruits) displayed the lowest Chl *a* + *b* content (39 mg kg^{-1} DW, on average), whereas 'Dolcenera' displayed the highest content (202 mg kg^{-1} DW) (Table 4).

The red-fruited cultivars had the highest TCC (354 mg kg^{-1} DW on average), with 'Fanello' exhibiting the highest carotenoids content (371 mg kg^{-1} DW) (Table 4), followed by the brownish and orange ones (286 mg kg^{-1} DW on average), whereas the yellow-fruited cultivars showed an average TCC almost 7.7-fold lower than that recorded in the red ones (Figure 3C). Consequently, the lowest TCC was recorded in '605156', 'Dolly', 'Ivorino', and 'Santy Yellow' (46 mg kg^{-1} DW, on average). As far as the other cultivars are concerned, 'Angelle' (red fruits) and 'Yuka' (orange fruits), along with 'Black Pearl', 'Dolcenera', and 'Top Zohar' (brownish fruits) displayed remarkably high TCC values (Table 4).

Table 4. Biochemical traits and antioxidant capacity related to the studied cultivars (mean ± standard error). Different letters within each column indicate significant differences between cultivars according to the Turkey's HSD test (p ≤ 0.05). NS: not significant; **, ***: significant at p ≤ 0.01 and 0.001,

Cultivar	TPC mg GAE kg^{-1} DW	Chl *a+b* mg kg^{-1} DW	Total carotenoids mg kg^{-1} DW	Lycopene mg kg^{-1} DW	DPPH % In.	FRAP mg TE kg^{-1} DW
'Angelle'	2940±69 bd	41.8±1.5 c	340±44 ab	217±24 a	81.3±4.4 ad	28.3±0.4 bd
'Fanello'	3296±35 ac	35.5±2.8 c	371±26 a	254±15 a	77.3±5.3 bd	26.8±1.1 bd
'605156'	3166±52 ac	42.5±14.5 c	35±3 f	n.d.	85.2±4.4 ad	27.9±1.7 bd
'Dolly'	2805±242 cd	45.5±3.1 c	61±3 f	n.d.	84.0±2.7 ad	27.2±1.2 bd
'Ivorino'	2939±290 bd	27.1±20 c	33±3 f	n.d.	83.0±5.4 ad	25.3±0.5 ce
'Santy Yellow'	3076±40 ad	34.9±4.8 c	55±4 f	n.d.	78.7±4.5 bd	26.9±1.6 bd
'Bamano'	2544±75 d	41.1±1.7 c	269±2 cd	n.d.	90.0±4.1 ac	21.5±0.6 e
'Blondy'	2496±62 d	44.7±4.2 c	196±12 e	n.d.	76.3±6.0 cd	28.7±0.4 ac
'Santy Naranja'	2734±114 cd	37.2±7.7 c	302±6 bd	n.d.	71.3±4.7 d	25.3±0.7 ce
'Yuka'	3283±22 ac	38.3±11.5 c	320±17 ac	n.d.	71.2±0.9 d	23.9±0.5 de
'Black Pearl'	2744±78 cd	148.2±5.3 ab	345±9 ab	106±4.0 b	92.7±1.0 ab	29.4±1.0 ac
'Dolcenera'	3155±51 ac	201.7±34.4 a	319±27 ac	108±19 b	85.5±3.8 ad	27.0±1.6 bd
'Melange'	3304±56 ac	142.3±23.2 ab	263±11 cd	90 ±10b	94.5±0.6 a	30.6±1.2 ab
'Thaiti'	3571±19 a	121.4±3.7 b	249±51 de	80 ±18b	86.5±4.3 ad	22.0±0.7 e
'Top Zohar'	3405±6 ab	172.4±1.1 ab	322±17 ac	107±3.0 b	90.3±1.0 ac	32.9±1.3 a
Mean	3030±52	78.3±9.1	232±19	137±12	83.2±1.4	26.9±0.5
$CV_{\%}$	10.6	76.9	53.3	49.9	8.7	11.3
F-test	8.11***	26.5***	99.11***	26.12***	5.27**	12.9***

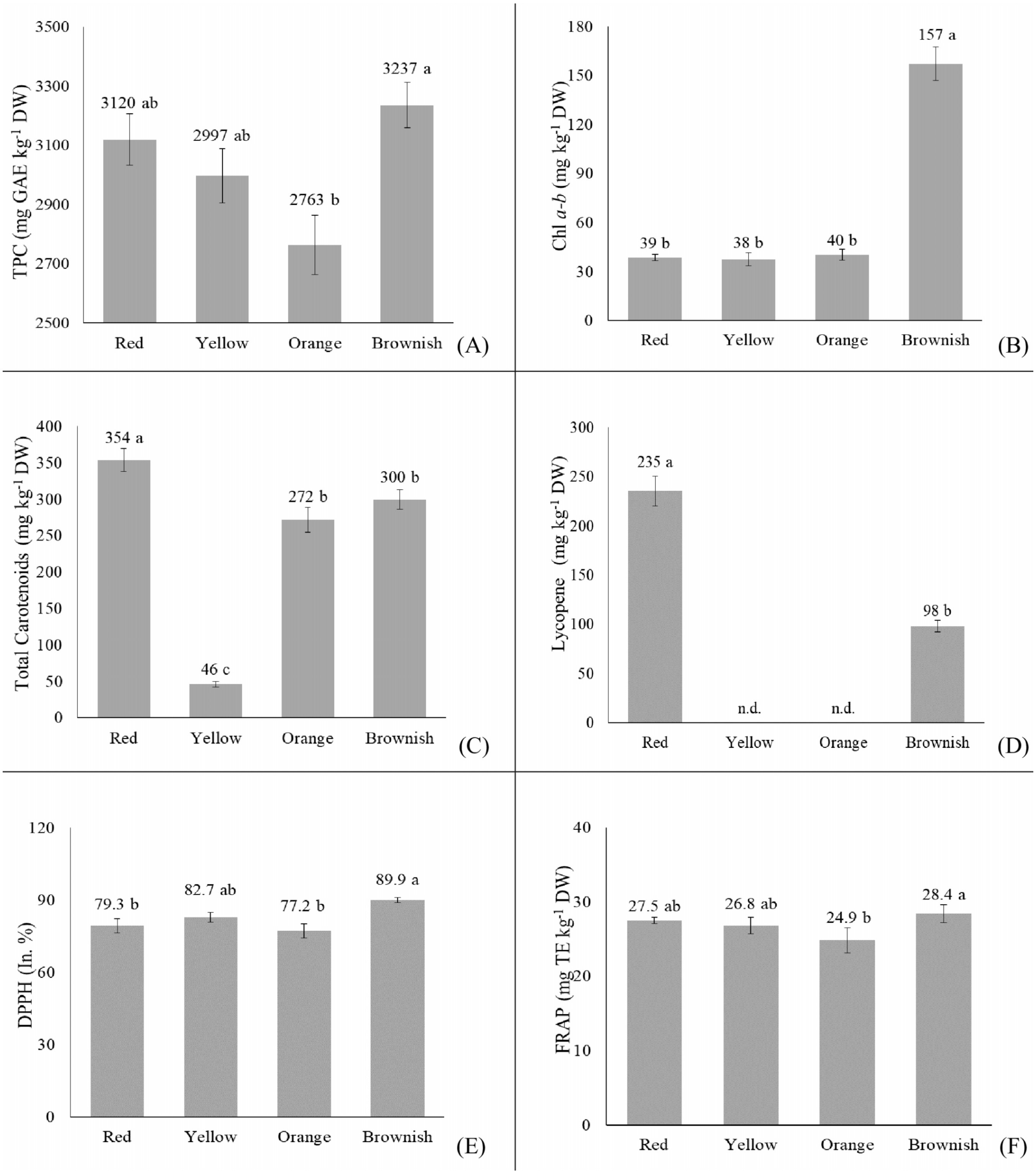

Figure 3. Contents of total polyphenols (A), chlorophyll *a* + *b* (B), total carotenoids (C) and lycopene (D), along with DPPH (E) and FRAP (F) of the studied cultivars grouped by fruit colour (mean ± standard error). Different letters indicate significant differences between fruit color groups according to the Turkey's HSD test ($p \leq 0.05$). n.d. = not detected.

Lycopene was detected only in red and brownish cultivars, with the red class displaying the highest content (235 mg kg^{-1} DW on average), that was 2.4-fold higher than that recorded in the brownish class (Figure 3C, Table 4). Lycopene content ranged between 80 mg kg^{-1} DW ('Thaiti') and 254 mg kg^{-1} DW ('Fanello') (Table 4).

3.3.3. DPPH and FRAP assay

Significant differences in DPPH were found among colour classes, as these values peaked in the brownish-fruited cultivars (89.9% In.), whereas lower values were measured in the red and orange groups (79.3% and 77.2% In., respectively) (Figure 3E). When cultivars were concerned, the average DPPH value was 83.2% In., varying between 71.2% In. (averaged over 'Santy Naranja' and 'Yuka') and 94.5% In. ('Melange') (Table 4). As for FRAP assay, significant differences were observed only between the orange and brownish classes (24.9 vs. 28.4 mg TE kg^{-1} DW on average, respectively). Referring to the cultivars, the highest value was observed in 'Top Zohar' (32.9 mg TE kg^{-1} DW), whereas 'Bamano' and 'Thaiti' displayed the lowest one (21.8 mg TE kg^{-1} DW, on average) (Table 4).

4. Discussion

Under the specific growing conditions of our experiment, the average marketable yield of the studied cultivars was 2.69 kg plant^{-1} (oscillating between 1.82 and 3.43 kg plant^{-1}). These values resulted slightly lower than those reported for greenhouse mini plum tomatoes by Rouphael et al., (2017) (3.5 kg plant^{-1}) and higher than those reported by Carillo et al., (2020). Marketable yield was a highly variable trait among cultivars, with some of them (i.e., 'Santy Yellow', 'Santy Naranja') performing better than the others, thanks to their higher total yield and/or lower incidence of discarded product. A very high incidence of discarded fruits was recorded in the case of 'Bamano' and 'Melange' (both higher than 20%, equal to 0.82 kg per plant, on average). The incidence of misshapen mini plum tomatoes can be attributed to different factors, including plant physiological disorders in response to non-optimal conditions (such as blossom end rot in response to high temperatures) (Hagassou *et al.*, 2019), and poor contemporaneity of fruit maturation within the cluster. These aspects are particularly noteworthy in cultivars designed for a premium tomato market, typically sold in specialized niches, where a flawless product is required. Consequentially, these varietal defects are often significant contributors to waste production over large-scale areas, contributing to exacerbate the environmental problems related to landfilling (Mauro et al., 2020).

Fruits handling can contribute to increasing waste production, as it can result in fruit lesions or reduction in their shelf-life. In many vegetables, a higher firmness is typically associated with a higher tolerance to mechanical injury along the supply chain, while a higher dry matter content and total soluble solids are associated with a reduced free water quantity, resulting in an extended shelf-life of the product (Giuffrida *et al.*, 2018). Consequently, among the novel cultivars assessed, those characterized by a high fruit firmness (i.e., 'Santy Yellow') and/or high dry matter content (i.e., 'Angelle', 'Santy Naranja', 'Melange', and 'Top Zohar') are expected to withstand handling, packaging, and transportation better than others.

TSS and TA are traits associated with tomato organoleptic descriptors such as the perceived sweetness (TSS) and sourness (TA) during fruit mastication. Tomato sugars (mainly fructose, glucose, and sucrose) are quantitatively the largest contributors to TSS, acting synergistically with other compounds such as organic acids (citric and malic) phenols and minerals, in influencing the overall fruit flavor perception (Raffo et al., 2002; Beckles, 2012). In our experiment, several cultivars, such as 'Angelle' (red fruits), 'Dolly' (yellow fruits), 'Bamano' and 'Blondy' (orange fruits) along with 'Thaiti' (brownish fruits), displayed high TSS values (varying from 8.86 to 10.20 °Brix), together with a wide range of TA (from 2.95 to 4.41 g CAE L^{-1}), thus having potential to satisfy a wide rage of consumers' taste preferences.

Tomato fruit colour is among the most important external characteristics which also greatly influences consumers' purchase decisions (Dorais et al., 2008; Bertin and Génard, 2018). In our study, the red-fruited cultivars displayed somewhat similar chromatic characteristics, while the opposite was found for the yellow ones. These latter cultivars displayed remarkably low values of the *a** chromatic coordinate (i.e., the red-green component), together with high values of hue angle, especially ‘605156’ and ‘Ivorino’. When compared to red fruits, both orange and brownish fruits displayed higher hue angle values, suggesting a lower contribution of the red hue in these tomatoes. Similar trends were also observed by Li et al. (2013) by comparing 13 tomato cultivars having pink, red, purple, yellow, or orange fruits.

Tomato fruits represent a prominent source of phytochemicals, including phenolics (e.g. rutin, naringenin), carotenoids (primarily lycopene and β-carotene), and vitamins (mainly vitamin A and C), all contributing to the important dietary role of this fruit vegetable (Slimestad and Verheulb, 2009; Choi et al., 2014; Distefano et al., 2022). These secondary metabolites exhibit a wide range of physiological activities, which attract an increasing consumers’ interest due to their health benefits (e.g. antioxidant, anti-mutagenic, and anti-inflammatory activities, among others) (Chaudhary et al., 2018). The content of these phytochemicals in the novel tomato cultivars represents a characteristic to consider to match the growing consumers’ demand for high-quality, nutrient-dense vegetables (Buturi et al., 2021, 2023; Martínez-Ispizua et al., 2022).

Despite the wide ranges observed for biochemical traits and antioxidant capacity, our results are in line with those reported in the literature by several authors (Campestrini et al., 2019; Distefano et al., 2020; Appolloni et al., 2023) on tomatoes produced under greenhouse conditions. Tomato fruits are rich in phenolic compounds and, to a lesser extent, chlorophylls. Phenolic compounds are a group of secondary metabolites that have significant antioxidant, anti-inflammatory, and anti-cancer properties, as well as potential benefits for cardiovascular health (Slimestad and Verheulb, 2009). Chlorophylls are lipid-soluble pigments widely present in plant-based foods, and they play a key role in the human diet. Indeed, their intake has been linked to multiple health benefits ranging from preserving the health of the circulatory and detoxification systems of the body counteracting toxins and inhibiting the activities of cancer-causing elements, positively influencing iron levels in human blood, and regulating blood sugar levels in the human body (Pareek et al., 2018; Shi et al., 2022). Moreover, chlorophyll degradation during fruit ripening is strongly associated with the tocopherols accumulation, a powerful fat-soluble antioxidant known as vitamin E (Mangialasche et al., 2012; Distefano et al., 2022). In our experiment, the brownish fruits exhibited the highest contents of total phenols and chlorophylls. Despite the fact that tomatoes have only moderate chlorophylls content when compared to other vegetables (Burns et al., 2003), their dietary importance suggests that even slight changes in their phytochemical composition can have significant influence on consumers’ phytochemicals intake (Mauro et al., 2020).

Carotenoids are one of the most widely studied phytochemical classes found in tomato. Besides their fundamental biological role in plants (e.g., light harvesting in photosynthetic membranes, pigment-protein complexes in thylakoids, precursors of abscisic acid) (Bertin and Génard, 2018), carotenoids have a wide range of biological activities in human body (e.g., antioxidant and free radical scavengers, modulate the pathogenesis of cancers and coronary heart disease). Among carotenoids, lycopene is one of the most well studied, not only because of its abundance in standard red tomatoes but also considering its distinctive nutraceutical properties that make it one of the most effective antioxidants among carotenoids (Distefano *et al.*, 2020). In our study, the total carotenoid content peaked in the red tomatoes, while all the yellow fruits displayed the lowest contents. This latter aspect may highlight a possible shared genetic background linked to decreased carotenoid accumulation as result of mutations in the genes governing the early steps of carotenogenesis (e.g., defective copies of phytoene synthase genes) (Chattopadhyay *et al.*, 2021). On the other hand although the orange and brownish fruits displayed a lower total carotenoids content than the red ones, some cultivars such as ‘Black Pearl’, ‘Dolcenera’ and ‘Top Zohar’ (brownish fruits), along with “Yuka” (orange fruits), outperformed the average total carotenoid of their colour group, exhibiting a content that was comparable to that of red tomato. Our study revealed that the content of lycopene was highest in red fruits, while yellow and orange fruits lacked lycopene altogether. Finally, brownish fruits had a lower content of lycopene, representing only one-third of all carotenoids. According to Burri et al. (2009) and Chattopadhyay et al. (2021), the presence of carotenoids different than lycopene can significantly influence and modify tomato functional traits. Hence, our findings suggest that the functional profile of these cultivars may significantly differ from that of red tomatoes due to different carotenoid composition. In this sense, it was reported that β-carotene, α-carotene, and β-cryptoxanthin act as provitamin A (a feature absents in lycopene), playing a key role in maintaining healthy skin and eyes, enhancing the immune system, and supporting organ function in the human body (Meng et al., 2022). Prolycopene, a highly bioactive and accessible form of lycopene, is responsible for the orange colour of tangerine tomatoes (Saini et al., 2020), and it is a compound able to influence the tomato functional profile (Jin et al., 2019; Saini et al., 2020). As reported by Burri et al. (2009), the consumption of tangerine tomato sauce, which mainly contained prolycopene, led to a higher increase in the total and tetra-cis-lycopene concentrations in blood compared to the red tomato sauce, despite the latter containing three times more total lycopene and total carotenoids. Similar results were also observed by Cooperstone et al. (2015) comparing tangerine and red tomato juice.

5. Conclusions

When novel cultivars are released on the market, acquiring information is valuable for farmers in relation to: their agronomic performance (e.g., marketable and total yield) to evaluate the potential profitability; the organoleptic and nutraceutical properties to determine the most suitable to market demands. In the light of these considerations, this work provided preliminary information about the productivity and nutritional quality of novel mini plum tomato cultivars grown under conventional greenhouse conditions and encompassing a range of fruit colours (red, yellow, orange, and brownish). The wide ranges of total soluble solids and titratable acidity observed suggest the potential to satisfy a broad range of consumers' preferences. Furthermore, cultivars among different colour groups exhibited potentially distinct nutraceutical characteristics, suggesting that their combined consumption could strengthen the prominent role of tomato in the Mediterranean diet. This approach would also address the increasing consumers' demand for high-quality and nutrient-dense vegetables. This aspect could have implications concerning the spread of tomatoes with high service content (e.g., chromatic assortment of tomato snacks). Finally, these results could contribute to further research that aims to accurately characterize the nutritional value of these novel cultivars for human nutrition.

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