

## Article

# Agronomic Comparisons of Heirloom and Modern Processing Tomato Genotypes Cultivated in Organic and Conventional Farming Systems

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**Abstract:** The yield and fruit quality of processing tomatoes (*Solanum lycopersicum* L.) have increased markedly over the past decades. The aim of this work was to assess the effects of the organic (OFS) and conventional farming systems (CFS) on the main agronomic parameters involved in processing tomato yield components and fruit quality traits of heirloom and modern genotypes. Marketable yield increased from heirloom to modern genotypes, both in OFS and in CFS, showing a difference of  $\approx 20$  t per hectare in favor of CFS. Total fruit yield (TY) was not improved from heirloom to modern assessed genotypes, and a difference of  $\approx 35$  t per hectare was observed in favor of CFS. In both farming systems, the highest marketable yield of modern genotypes was due to a higher number of fruits per plant, harvest index, nitrogen agronomic efficiency (NAE), and fruit water productivity. Moreover, the main growth parameters involved in the yield differences between OFS and CFS were the number of leaves per plant, the average fruit weight, the normalized difference vegetation index (NDVI), and NAE. It is noteworthy that fruit quality improvement in terms of color and brix per hectare was paralleled by a decrease of tomato pH in both farming systems. According to our results, we conclude that to reduce the current yield gap between OFS and CFS, agronomic and breeding efforts should be undertaken to increase leaf area index, fruit number per plant, and NAE for better genotype adaptation to organic farming systems.

**Keywords:** farming systems; yield; quality; fruit; harvest index; Brix; NDVI

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## 1. Introduction

Tomato (*Solanum lycopersicum* L.) is an economically important crop for the global agricultural sector. During the last 30 years, the tomatoes produced worldwide for the canning industry increased from 22 to 37.8 million tonnes (+72%) [1]. Over the 1997–2017 period, there was a yield increase of 60%, with an annual growth rate close to 2.4%. The main factors of this impressive variation are mainly due to (i) genotype improvement, (ii) careful management of resources and inputs, and (iii) application of good agronomic practices [1]. According to World Processing Tomato Council (WPTC) data, Italy is the second-largest producer of processing tomato in the world [1].

Not long ago, environmental sustainability and food safety became key policy objectives for all European countries. The reduction of the use of external inputs, such as plant protection products and fertilizers, and the increase of agricultural land areas, in which organic production rules are applied, are the principal means to achieve these objectives.

However, published studies on organic (OFS) versus conventional farming systems (CFS) displayed a lower yield of some crops, such as tomato, soybean, corn, winter wheat,

and winter rye, in the OFS [2,3]. Some researchers explained the lowest yield in the OFS as results of the lower soil nitrogen (N) availability, the higher incidence of diseases (fungi and bacteria), and the development of weeds [4,5].

In order to increase the tomato production sustainability, viable alternatives to synthetic plant protection products and fertilizers, such as essential oil, digestate, biochar, and compost tea, were investigated [6,7]. In a recent work, Ronga et al. [8] found that the combined use of biochar and digestate increased the marketable yield of processing tomato under OFS. The use of cover crops, such as hairy vetch (*Vicia villosa* Roth.), subclover (*Trifolium subterraneum* L.), and oat (*Avena sativa* L.) cultivated in winter and used as dead mulch in spring, can reduce tomato yield losses while limiting the presence of weed [9]. A field experiment on organic processing tomato, performed to find alternative mulch materials [10], found that biodegradable plastic mulch and the polyethylene mulch treatments had similar values and a higher performance in comparison with bare soil in term of weed control, early fruit development, total dry weight, total fruit weight, and number of fruits *per* plant. A study on grafting technique reported that the use of commercial rootstock increased the marketable yield, fruit number, and fruit weight of local “Moruno” populations (Mor-62, Mor-204) in the OFS [11]. Recently, Caradonia et al. [12] observed that the combined use of grafting and microbial biostimulants increased the marketable and total yield of a commercial processing tomato genotype ‘H3402’ and reduced the number of fruits affected by blossom-end rot.

Although many studies have been performed or are underway in order to find alternative and sustainable external inputs, nowadays, few works focus on the identification of elite genotypes tailored for the production under OFS [3]. In addition, to the authors’ knowledge, no study on the identification of the main traits involved in the yield components of heirloom and modern genotypes has been reported for the OFS. In fact, as reported by Le Campion et al. [13], breeders did not take enough efforts in developing genotypes suitable to be cultivated in the OFS in the last few years. Even though this aspect could represent a key solution to achieve a higher yield and to reduce the OFS vs. CFS yield gap [14], no available reports are present in the literature. According to Lammerts van Bueren et al. [15], organic farmers often use genotypes bred for conventional systems. These genotypes require high levels of various synthetic external inputs to achieve the yield potential and show at the same time low competitive capacity against weeds and limited resilience to abiotic and biotic stresses. Therefore, they are not suitable to be cultivated in the low input farming system and obviously in the OFS. Local varieties could represent an alternative, as they are better adapted to specific agroclimatic conditions and less dependent on external inputs [16]. Moreover, they can perform well in a specific area, because genotypes bred for OFS can maximize the genotype × environment interaction. For the development of a specific breeding program, it is essential to know the traits associated with the low/high productivity. The exploitation of heirloom and modern genotypes and their comparison could help reach these objectives. Interestingly, Anastasi et al. [14] reported that favorable alleles for traits of interest in the OFS could be found in heirloom genotypes. In a previous report, Ronga et al. [3] assessed six modern genotypes of processing tomato commonly cultivated in Southern Italy and attributed the yield reduction in a lower leaf area that led to a reduction of total biomass dry weight. However, in the same study, only modern genotypes were cultivated [3]; therefore, we do not have information about the agronomic traits of heirloom genotypes putatively suitable to increase the processing tomato yield in the OFS. Considering all the above-mentioned issues, a field study, in OFS and in CFS, was carried out in the present study to compare five processing tomato genotypes released and cultivated in Italy over the last 90 years. The objective was to identify the main agronomic traits suitable to achieve a higher processing tomato yield and fruit quality in OFS. This information might be used in the design of specific breeding programs aimed at the development of new genotypes suitable for the OFS and able to reduce the current processing tomato yield gap between OFS and CFS.

## 2. Materials and Methods

### 2.1. Field Experiments

Five representative genotypes of processing tomato, cultivated in Italy in the last decades [17], were assessed in open field trials both under OFS and CFS. The seeds of the genotypes were kindly provided by a local seed company (ISI Sementi S.p.A., Fidenza, Italy). The main characteristics of the genotypes are presented in Table 1 in accordance with Ronga et al. [18] and P. Passeri (ISI Sementi S.p.A.) personal communication.

**Table 1.** Characteristics of the genotypes used in the present study.

Genotype	Year of Release	Growth Habit	Fruit Characteristics
PEARSON	mid-1930s	Self-topping, semi-determinate, with dense foliage	globular and large fruits
C33	early-1970s	short bush, determinate	globular and large fruits
E6203	1984	determinate, with abundant flowering	medium blocky fruit
BRIGADE	1989	determinate, rustic	highly productive, with medium blocky fruit
H3402	2002	determinate, rustic, bushy with high plant vigor	high fruit production, with medium oval fruit

### 2.2. Growth Condition

In 2018, an open field study was performed in two locations of the Po Valley (Emilia-Romagna Region, Northern Italy) at Reggio Emilia, for the OFS (44°41'18.6" N 10°34'11.8" E, 78 m a.s.l.) and Fidenza for the CFS (44°50'58.5" N 10°02'10.8" E, 75 m a.s.l.). For the OFS, the site has been managed organically since 1985 according to the EU Regulation and the guidelines of the Emilia–Romagna Region (Italy); the previous crop was bread wheat. Conversely, for the CFS, the site has always been managed conventionally according to the guidelines of the Emilia–Romagna Region (Italy), the field was not fumigated before the trial, and the previous crop was bread wheat. The weather conditions were typical of the continental climate: in the OFS and in the CFS, the minimum and the maximum average temperatures recorded were 18.1 and 16.9 °C and 29.6 and 29.3 °C, respectively, and the rainfalls occurred from transplanting to harvest were 279.2 and 274.2 mm, respectively. In both farms, the soil was well-drained and classified as Alfisoloil, according to the American classification of Soil Taxonomy [19] characterized by a clay-loam texture (Table 2).

**Table 2.** Physical and chemical soil properties of the two farming systems. EC = electrical conductivity; TN = total nitrogen; CEC = cation exchange capacity.

Soil Characteristics	OFS	CFS
Sand (%)	11.2	9.9
Silt (%)	67.5	57.4
Clay (%)	21.3	32.7
pH	7.8	8.1
EC (dS m <sup>-1</sup> )	0.2	0.1
Exchangeable K <sub>2</sub> O (mg kg <sup>-1</sup> ) (ammonium acetate method)	179.9	285.4
P <sub>2</sub> O <sub>5</sub> (mg kg <sup>-1</sup> ) (Olsen method)	55.0	51.2
TN (‰) (Kjeldahl method)	1.3	1.5
Organic matter (%)	1.8	1.2
CEC (meq 100 g <sup>-1</sup> )	17.9	21.4

In both farms, seedlings (6-week-old plants, fourth true leaf stage) were transplanted at the beginning of May. Plant density was maintained identical, at 3.1 plants m<sup>-2</sup>, for all tested genotypes and in each investigated environment. Seedlings were transplanted into single rows, 0.20 m between plants and spaced in rows 1.60 m apart. Each site was arranged in a completely randomized design with three replications *per* genotype; two border rows were planted for each plot. Plots were 5.0 m long × 4.2 m wide and contained 65 plants. All genotypes were cropped following standard modern agronomic practices for OFS (EU Regulation and guidelines of the Emilia–Romagna Region, Italy) and CFS (guidelines of the Emilia–Romagna Region, Italy). Regarding fertilization in CFS, 150 kg of N ha<sup>-1</sup>, 194 kg of P ha<sup>-1</sup>, and 258 kg of K ha<sup>-1</sup> were applied. Nitrogen (as ammonium nitrate) was applied 33% at transplant and 67% (as calcium nitrate) from full flowering to fruit ripening, whereas P and K were applied one month before the planting time. In the OFS, seven months before transplanting, mature cow manure (40 t ha<sup>-1</sup>; N, 0.5%; P, 0.1% and K, 0.3%, reported as fresh matter) was applied to the soil prior ploughing. In both cropping systems, drip irrigation was used to distribute water. Irrigation volumes were calculated from the total water lost by evapotranspiration according to the formula:  $ET_c = ET_o \times K_c$ , where  $ET_o$  (estimated according to the Hargreaves equation) is the reference evapotranspiration and  $K_c$  (0.4 at transplanting; 0.6 until flowering; 0.8 at flowering; 1.0 at fruit set; 1.05 at fruit development; 0.9 at fruit ripening; 0.6 at fruit maturity) is the crop coefficient of tomato [20]. When the soil was depleted to 40% of total available water, 100%  $ET_c$  was restored in agreement with the evapotranspiration method of Doorenbos and Pruitt [21]. Weeds and pests were controlled following the production rules of Emilia–Romagna Region, Italy. In particular, weeds were controlled chemically in the CFS and mechanically in the OFS. As regards the pathogen and pest control, fungicides (sulfur, copper oxychloride, difenoconazole and fosetyl–aluminium) and pesticides (azadirachtin A, imidacloprid, spinosad, abamectin, and emamectin benzoate) were used in the CFS, whereas only sulfur and copper oxychloride were used in the OFS. A single harvest was carried out at the end of the growing seasons, i.e., within the first ten days of September, when ripe fruits were at least approximately 85% of the total fruits.

### 2.3. Recorded Parameters

Starting one month after transplanting, morphological, physiological, and fruit quality traits were assessed in four plants *per* plot. The traits were recorded at the following stages: (i) full flowering (stage 6.3); (ii) beginning of fruit development (stage 7.1); (iii) fruit and seed ripening (stage 8.1); and (iv) fruit maturity (stage 8.9) [22]. The traits were divided into three categories (morphological, physiological, and fruit quality). Morphological (non-destructive) and physiological traits were assessed at each crop stage, whereas morphological (destructive) traits, such as biomass and fruit quality, were assessed only at harvest time. For morphological characterization, leaf (NL) and fruit (FN, counting unripe and ripe) number and plants height (PLH) were recorded at each sampling time. At harvest, leaf area index (LAI) was measured using a subsample of fresh leaves that were run through the leaf area meter LI-3000A (LI-COR Inc., Nebraska, USA). Marketable fruit yield (MY, considering only the fresh weight of ripe fruit), average fruit weight (AFW, considering only full ripe fruit), total fruit yield (TY as the sum of the fresh weight of unripe and ripe fruits) were recorded, and harvest index (HI) was calculated. Regarding the physiological characterization, the index of leaf chlorophyll content (SPAD) was estimated on the youngest fully expanded leaf by SPAD-502 (Minolta, Japan). At canopy level, normalized difference vegetation index (NDVI) was measured by an SRS-NDVI (Decagon Device, Pullman, WA, USA) instrument. The measurements were taken at 1 m above the canopy. Ten average spectra, each a mean of 10 spectra, were recorded *per* plot. In order to compare N use among genotypes, the nitrogen agronomic efficiency (NAE) index was calculated as the ratio between the marketable fruit yield (t ha<sup>-1</sup>) and the amount of N applied (kg ha<sup>-1</sup>) [23]. Fruit water productivity (FWP) was also calculated as

the ratio between the marketable yield (kg) and the total water used by plants (mm) during the growing season [24]. Finally, a subsample of fresh fruits ( $\approx 35$  tomatoes), using a cold break preparation, was used to assess the fruit quality. The following traits were evaluated: pH, total soluble solid content ( $^{\circ}$ Brix), and color. The pH was measured with a Basic 20 pH-meter (Crison, Instrument, Barcelona, Spain), whereas  $^{\circ}$ Brix were determined using a digital refractometer (HI 96814, Hanna Instruments, Villafranca Padovana, Italy). Pulp color was assessed using a Gardner XL-23 tristimulus colorimeter (Gardner Laboratory Inc., Bethesda, MD, USA), values are reported as the ratio of chromaticity indices "a" (redness) over "b" (yellowness). Moreover,  $^{\circ}$ Brix yield (BY) was determined by multiplying the marketable yield ( $\text{t ha}^{-1}$ ) by the  $^{\circ}$ Brix value and dividing by 100 and was expressed as the amount of soluble solids *per* ton of marketable yield *per* ha ( $\text{t ha}^{-1}$ ).

#### 2.4. Data Analysis

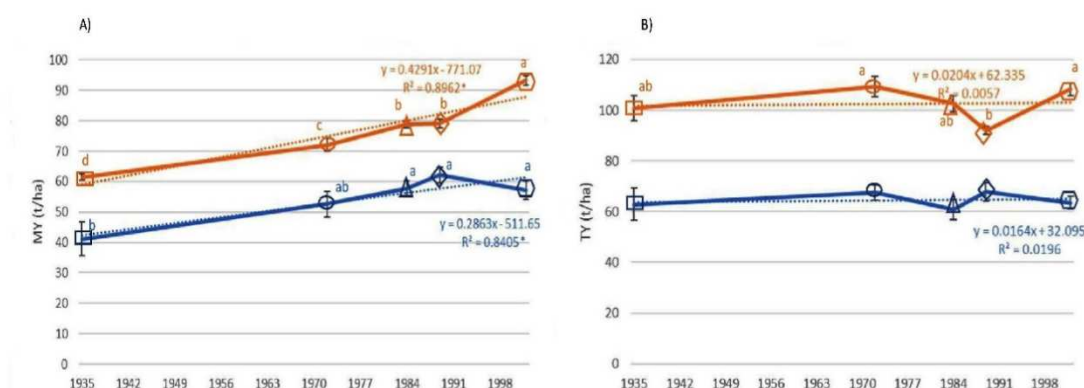
The figures displayed in the present study show the traits assessed in each genotype and in each farming system as an average of values recorded at each timing. For each investigated trait, a regression analysis was performed. The regression coefficient was evaluated for statistical difference from zero by F tests. In addition, genotype differences were investigated by ANOVA and Tukey test (at  $p < 0.05$ ) used to compare treatment. Finally, a Principal Component Analysis (PCA) was performed, using for each genotype the average values of replicates; then, results were presented as biplots. Statistical analysis was performed with GenStat 17th software.

### 3. Results

#### 3.1. Fruit yield

In both the cropping systems, considering only ripe and marketable fruits, yield increased significantly in modern genotypes ( $R^2 = 0.89$  in the CFS and  $0.84$  in the OFS) (Figure 1A). In the CFS, the highest marketable yield was shown by the most modern genotypes "H3402" (+51%) compared to the oldest one "PEARSON". In the same way, in the OFS, the lowest marketable yield was displayed by genotype "PEARSON", whereas genotypes "E6203", "BRIGADE", and "H3402" recorded the highest marketable yield (on average +50%) compared to the oldest one. In addition, between the two farming systems, the investigated genotypes showed a gap of  $\approx 20 \text{ t ha}^{-1}$ , lower in the OFS, apart for genotype "H3402", which reported a gap of  $\approx 30 \text{ t ha}^{-1}$ .

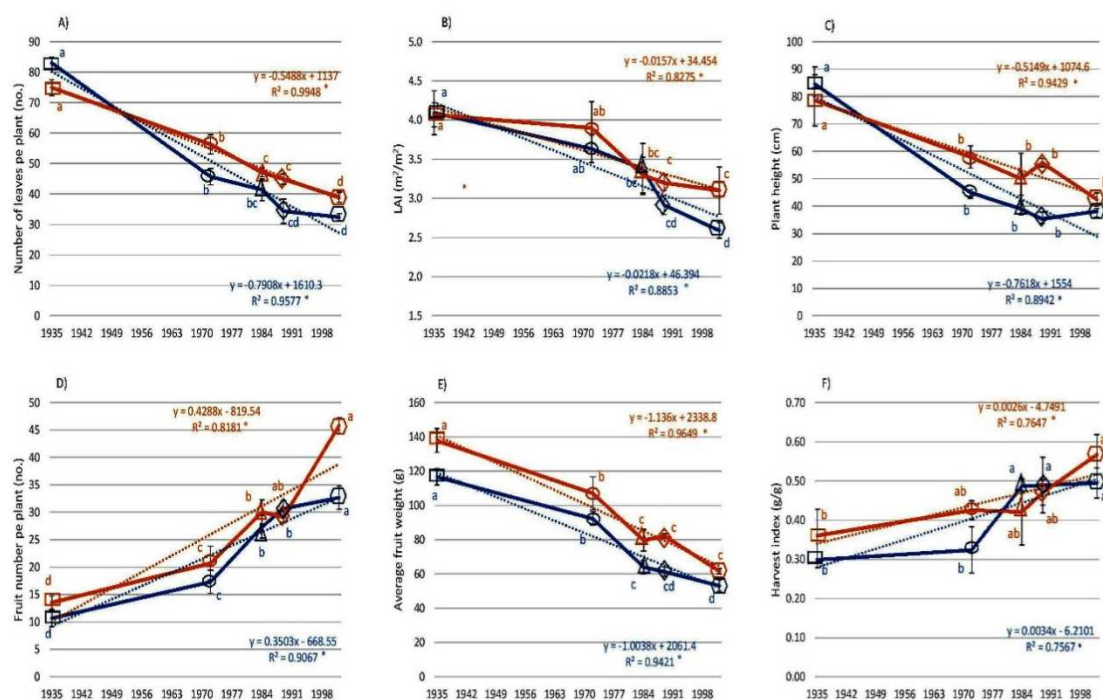
In both the farming systems, considering all fruits (unripe and ripe) *per* plant, the total fruit yield did not increase with the year of release of the assessed genotypes, and no difference was observed among the genotypes cultivated in the OFS. Conversely, in the CFS genotype, "BRIGADE" showed the lowest value of total yield (Figure 1B). In general, between the two farming systems, the cultivated genotypes showed a gap of  $\approx 40 \text{ t ha}^{-1}$ , lower in the OFS, apart for genotype "BRIGADE", which reported a gap of  $\approx 25 \text{ t ha}^{-1}$ .



**Figure 1.** Marketable (A) and total (B) yields. Regression is shown as a dotted line (orange and blue for the conventional and organic farming systems, respectively), while different symbols indicate the tested genotypes (PEARSON = rectangle, C33 = ellipse, E6203 = triangle, BRIGADE = rhombus, H3402 = hexagon). Superscript lowercase letters indicate significant differences (Tukey's test  $p < 0.05$ ); bars represent standard error; \* = significant correlation at  $p < 0.05$ .

### 3.2. Morphological Traits

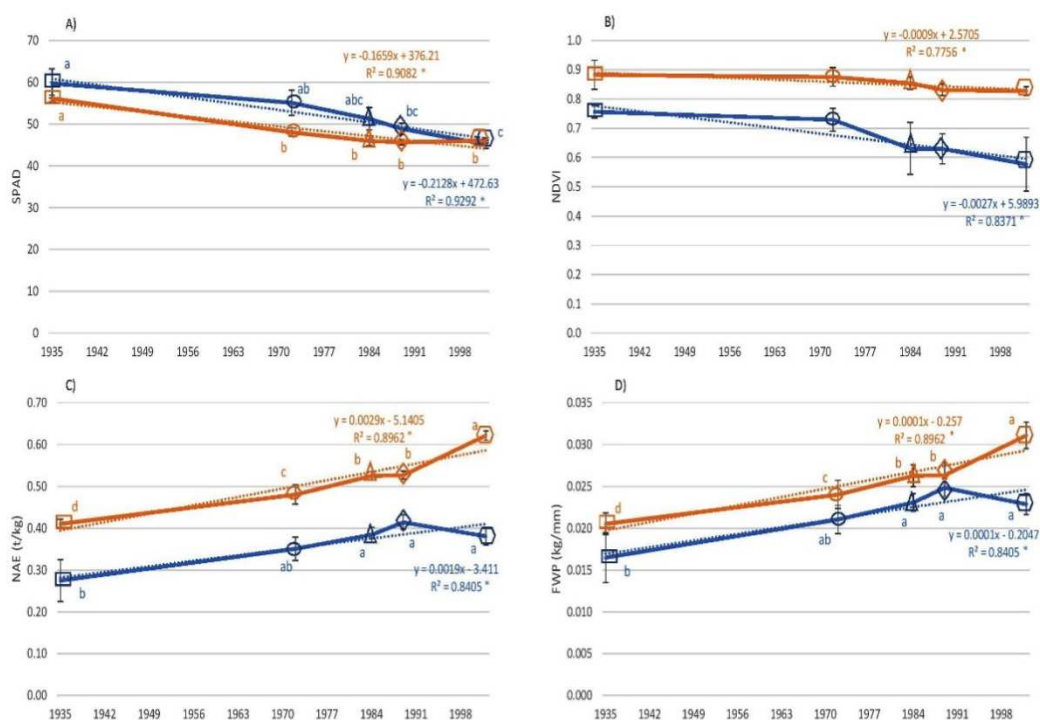
As summarized in Figure 2, six morphological traits, important for the processing tomato crop, were measured: leaf number *per plant*, leaf area index, plant height, fruit number *per plant*, average fruit weight and harvest index. In both cropping systems, leaf number *per plant* (Figure 2A), leaf area index (Figure 2B), plant height (Figure 2C), and average fruit weight (Figure 2E) showed a reduction linked with the year of release of the assessed genotypes ( $R^2 = 0.96, 0.86, 0.89,$  and  $0.94$  in the CFS and  $R^2 = 0.99, 0.83, 0.94,$  and  $0.96$  in the OFS, respectively). Leaf number *per plant* decreased from  $\approx 75$  (in the oldest genotype) to  $\approx 40$  (in the most modern one) in the CFS, whereas decreased from  $\approx 85$  (in the oldest genotype) to  $\approx 30$  (in the most modern one) in the OFS (Figure 2A). Leaf area index decreased from  $\approx 4$  (in the oldest genotype) to  $\approx 3$  (in the modern one) in the CFS, whereas it decreased from  $\approx 4$  (in the oldest genotype) to  $\approx 2.5$  (in the most modern one) in the OFS (Figure 2B). Plant height decreased from  $\approx 80$  cm (in the oldest genotype) to  $\approx 40$  cm (in the most modern one) in the CFS, whereas it decreased from  $\approx 85$  cm (in the oldest genotype) to  $\approx 40$  cm (in the most modern one) in the OFS (Figure 2C). Average fruit weight decreased from  $\approx 140.0$  g (in the oldest genotype) to  $\approx 60.0$  g (in the most modern one) in the CFS, whereas it decreased from  $\approx 120.0$  g (in the oldest genotype) to  $\approx 55.0$  g (in the most modern one) in the OFS (Figure 2E). On the other hand, fruit number *per plant* (Figure 2D) and harvest index (Figure 2F) increased with the year of release of the investigated genotypes ( $R^2 = 0.91$  and  $0.76$  in the CFS and  $0.82$  and  $0.76$  in the OFS, respectively). Fruit number increased from  $\approx 15$  (in the oldest genotype) to  $\approx 45$  (in the most modern one) in the CFS, whereas it increased from  $\approx 10$  (in the oldest genotype) to  $\approx 33$  (in the most modern one) in the OFS (Figure 2D). Finally, harvest index increased from  $\approx 35$  (in the oldest genotype) to  $\approx 55$  (in the most modern one) in the CFS, whereas it increased from  $\approx 0.30$  (in the oldest genotype) to  $\approx 0.50$  (in the most modern one) in the OFS (Figure 2F).



**Figure 2.** Morphological traits. Number of leaves (A), leaf area index (B), plant height (C), fruit number (D), average fruit weight (E), harvest index (F). Regression is shown as a dotted line (orange and blue for the conventional and organic farming systems, respectively), while different symbols indicate the tested genotypes (PEARSON = rectangle, C33 = ellipse, E6203 = triangle, BRIGADE = rhombus, H3402 = hexagon). Superscript lowercase letters indicate significant differences (Tukey's test  $p < 0.05$ ); bars represent standard error; \* = significant correlation at  $p < 0.05$ .

### 3.3. Physiological Traits

As reported in Figure 3, four physiological traits were recorded in the present study: SPAD, NDVI, NAE, and FWP. All characters were correlated with the year of release of the assessed genotypes. Each investigated trait, apart from NDVI, highlighted interesting differences among the cultivated genotypes. In both cropping systems, SPAD (Figure 3A) and NDVI (Figure 3B) showed a reduction linked with the year of release of the assessed genotypes ( $R^2 = 0.93$  and  $0.84$  in the CFS and  $0.91$  and  $0.78$  in the OFS, respectively). Conversely, NAE (Figure 3C) and FWP (Figure 3D) reported an increase of the values ( $R^2 = 0.84$  and  $0.84$  in the CFS and  $0.90$  and  $0.90$  in the OFS, respectively). SPAD decreased from  $\approx 55$  (in the oldest genotypes) to  $\approx 45$  (in the most modern one) in the CFS, and from  $\approx 60$  (in the oldest genotype) to  $\approx 45$  (in the most modern one) in the OFS. NDVI decreased from  $\approx 0.9$  (in the oldest genotype) to  $\approx 0.8$  (in the most modern one) in the CFS, and from  $\approx 0.8$  (in the oldest genotype) to  $\approx 0.6$  (in the most modern one) in the OFS. On the other hand, NAE and FWP increased from  $\approx 0.4$  and  $0.02$  (in the oldest genotype, respectively) to  $\approx 0.6$  and  $0.03$  (in the most modern one, respectively) in the CFS and from  $\approx 0.3$  and  $0.017$  (in the oldest genotype, respectively) to  $\approx 0.4$  and  $0.022$  (in the most modern one, respectively) in the OFS.



**Figure 3.** Physiological traits. SPAD = index of chlorophyll content in leaf (A), NDVI = normalized difference vegetation index (B), NAE = nitrogen agronomic efficiency (C), FWP = fruit water productivity (D). Regression is shown as a dotted line (orange and blue for the conventional and organic farming systems, respectively), while different symbols indicate the tested genotypes (PEARSON = rectangle, C33 = ellipse, E6203 = triangle, BRIGADE = rhombus, H3402 = hexagon). Superscript lowercase letters indicate significant differences (Tukey's test  $p < 0.05$ ); bars represent standard error; \* = significant correlation at  $p < 0.05$ .

### 3.4. Fruit Quality Traits

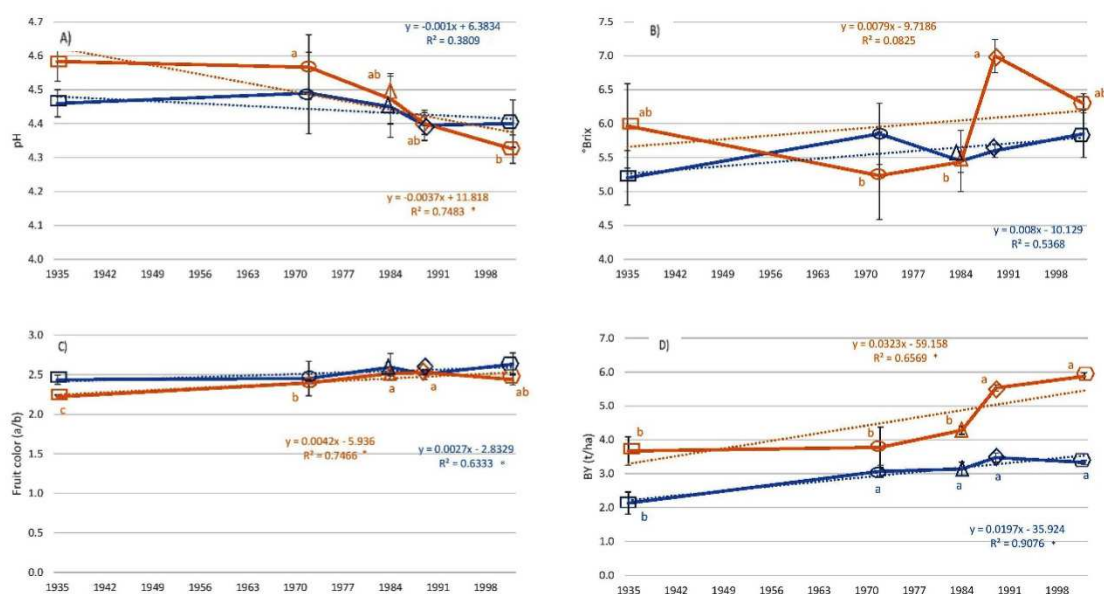
The results regarding fruit quality traits—pH, °Brix, fruit color, and °Brix yield—are shown in Figure 4. Fruit color and °Brix yield showed an increase linked with the year of release of the investigated genotypes. Genotypes were different for all the investigated traits in the CFS, whereas in the OFS, they only differed for BY. The year of release of the investigated genotypes was positively correlated with fruit color and BY ( $R^2 = 0.63$  and  $0.91$  in the CFS and  $0.75$  and  $0.66$  in the OFS, respectively), while it was negatively correlated ( $R^2 = 0.74$ ) with pH only in the OFS (Figure 4). Fruit color increased from  $\approx 2.2$  (in the oldest genotype) to  $\approx 2.4$  (in the most modern one) in the CFS, and from  $\approx 2.4$  (in the oldest genotype) to  $\approx 2.6$  (in the most modern one) in the OFS. In the CFS, genotypes “E6203” and “BRIGADE” showed the highest value of fruit color, whereas no differences were detected between the genotypes in the OFS (Figure 4C).

BY increased from  $\approx 4.0$  (in the oldest genotype) to  $\approx 6.0$  (in the most modern one) in the CFS, and from  $\approx 2.0$  (in the oldest genotype) to  $\approx 3.5$  (in the most modern one) in the OFS. In the CFS, genotypes “H3402” and “BRIGADE” showed the highest value of BY, whereas genotype “PEARSON” displayed the lowest ones in the OFS (Figure 4D).

pH decreased from  $\approx 4.6$  (in the oldest genotype) to  $\approx 4.3$  (in the most modern one) in the CFS, and from  $\approx 4.5$  (in the oldest genotypes) to  $\approx 4.4$  (in the most modern one) in the OFS. In the CFS, genotype “H3402” showed the lowest value of pH, whereas no differences were detected between the genotype in the OFS (Figure 4A).

Brix was not correlated with year of release; however, genotype “BRIGADE” showed the highest value in the CFS, whereas no differences were displayed among the genotypes cultivated in the OFS.





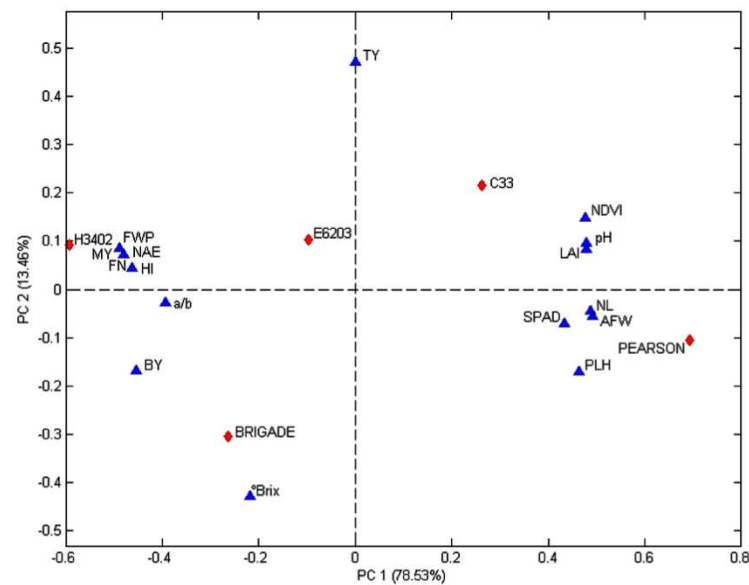
**Figure 4.** Fruit quality traits. pH (A), °Brix (B), fruit color (C), BY = brix t ha<sup>-1</sup> (D). Regression is shown as a dotted line (orange and blue for the conventional and organic farming systems, respectively), while different symbols indicate the tested genotypes (PEARSON = rectangle, C33 = ellipse, E6203 = triangle, BRIGADE = rhombus, H3402 = hexagon). Super-script lowercase letters indicate significant differences (Tukey's test  $p < 0.05$ ); bars represent standard error; \* = significant correlation at  $p < 0.05$ .

### 3.5. Principal Component Analysis

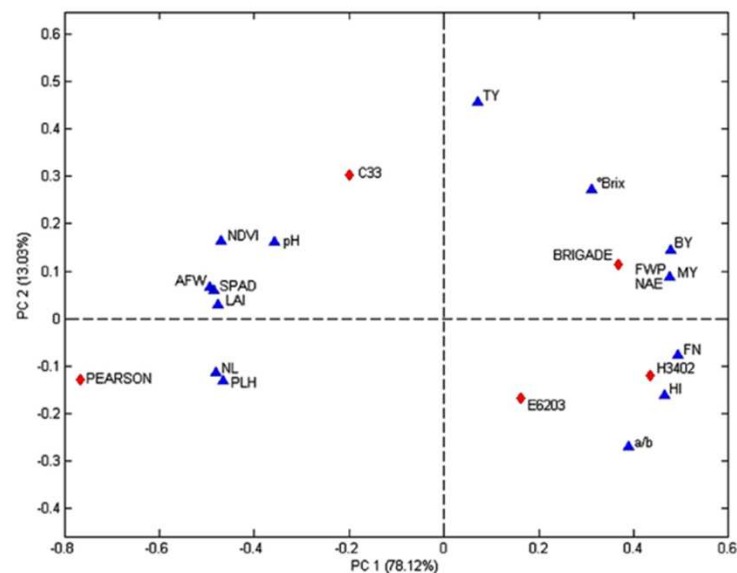
All recorded data were analyzed using PCA to determine the corresponding association between assessed traits and genotypes. The resulting ordination biplots for CFS and OFS are shown in Figures 5 and 6, respectively.

In Figure 5, PC1 accounted for 78.53% of the variance, PC2 accounted for 13.46%, and their sum explained 91.99% of total variance. PC1 clearly separates modern genotypes from old ones. In fact, modern genotypes are all on the negative quadrant, whereas old ones are all on the positive quadrant of PC1. Morphological and fruit quality traits were the main drivers of the PC1 and PC2, respectively. Among the modern genotypes, "H3402" and "BRIGADE" were positively associated with high values of FWP, NAE, BY, MY, FN, HI, a/b, and °Brix. On the other hand, old genotypes were positively linked to high values of NDVI, pH, AFW, SPAD, LAI, NL, and PLH.

Figure 6 shows ordination biplots of the PCA for OFS. PC1 accounted for 78.12% of the variance, PC2 accounted for 13.03%, and their sum explained 91.15% of total variance. PC1 clearly separates modern genotypes from old ones. Modern genotypes are all on the positive quadrant, whereas old ones are all on the negative quadrant of PC1, respectively. Morphological and the fruit quality traits were the main drivers of the PC1 and PC2, respectively. In particular, among the modern genotypes, "H3402" and "BRIGADE" were positively associated with high values of FWP, NAE, BY, MY, FN, and HI. On the other hand, "genotypes Pearson" and "C33" were positively linked to high values of NDVI, pH, AFW, SPAD, LAI, NL, and PLH.



**Figure 5.** Ordination biplot for the principal component analysis outputs for the conventional cropping system. Red rhombus indicates the assessed genotypes, while blue triangle indicates the investigated traits. NL = number of leaves, SPAD = index of chlorophyll content in leaf, PLH = plant height, NDVI = normalized difference vegetation index, LAI = leaf area index, FN = fruit number, AFW = average fruit weight, BY = brix  $t\ ha^{-1}$ , a/b = fruit color, HI = harvest index, MY = marketable yield, FWP = fruit water productivity, NAE = nitrogen agronomic efficiency, TY = total yield.



**Figure 6.** Ordination biplot for the principal component analysis outputs for the organic cropping system. Red rhombus indicates the assessed genotypes, while blue triangle indicates the investigated traits. NL = number of leaves, SPAD = index of chlorophyll content in leaf, PLH = plant height, NDVI = normalized difference vegetation index, LAI = leaf area index, FN = fruit number, AFW = average fruit weight, BY = brix  $t\ ha^{-1}$ , a/b = fruit color, HI = harvest index, MY = marketable yield, FWP = fruit water productivity, NAE = nitrogen agronomic efficiency, TY = total yield.

#### 4. Discussion

In organic tomato production, the identification of elite genotypes suitable for a sustainable cultivation could represent a crucial solution to achieve eligible yield with respect to conventional production systems [3,14].

Although in the last years, significant breeding efforts have been conducted for improving tomato crop performance, suitable materials to be cultivated in the OFS are limited in number and not enough for all the dedicated agricultural areas [13]. In fact, the organic sector asks genotypes bred for low input farming, adapted to local conditions, and it often aims for specific quality parameters. In the present study, the main traits of heirloom and modern genotypes, influencing yield and quality of processing tomato, were assessed under OFS for the first time in Italy, which is one of the most important countries for tomato production and consumption [25]. Accordingly, five processing tomato genotypes released and cultivated over the last 90 years were compared in the OFS and in the CFS in a field study using the modern agronomic management allowed in the respective systems.

The yield of a crop in a specific area is influenced by genetic, technological, biological, and environmental factors interacting with each other [26]. A crop management that increases productivity, resilience, and food security in a safe way is the baseline goal of sustainable agriculture [27]. Taking into account these considerations, the present study allows an estimation of the genetic gains by studying genotypes released in past decades and cropped with the same agronomic management.

As shown in the Figure 1, from heirloom to modern genotypes, total yield was not improved both in OFS and in CFS, and an average gap of  $\approx 35$  t *per* hectare between the two farming systems was displayed in favor of the CFS. On the contrary, when only marketable fruits were considered, an increase of yield was observed from heirloom to modern genotypes both in OFS and in CFS, and a gap of  $\approx 20$  t *per* hectare between the two farming systems was observed in favor of the CFS. Modern genotypes gained the highest marketable yield for both systems due to a higher number of fruits *per* plant (Figure 2D) and harvest index (Figure 2F) as morphological traits, and nitrogen agronomic efficiency (Figure 4C) and fruit water productivity (Figure 4D) as physiological ones. Our results on morphological traits are in agreement with other studies that investigated processing tomato genotypes suitable for the Californian [28] and Italian [17] environments, which both performed under conventional farming system. Moreover, our findings indicate that different traits contribute together to a yield increase of processing tomato genotypes [29], although different fertilization inputs were adopted between the two investigated cropping systems (i.e., organic vs. conventional).

An increase in HI could represent a good opportunity for a yield improvement, especially when it is due to a maximization of harvestable fruit with a reduction of green and spoiled fruits [28]. Interestingly, from heirloom to modern genotypes, HI increased more in the OFS than in the CFS and genotypes “E6203” and “BRIGADE” performed better in the OFS than in the CFS (Figure 2F). In particular, two important traits are related to HI: LAI and fruit number. The genotypes “E6203” and “BRIGADE” displayed similar values of LAI (Figure 2B) and number of fruits *per* plant (Figure 2D) in OFS vs. CFS. These results suggest that these genotypes were able to produce a balanced total biomass to guarantee a good distribution of photosynthates among different organs reaching a general good crop growth in both the investigated cropping systems.

Indices based on light reflectance in the red and near infrared regions of the spectrum (NDVI, and SPAD chlorophyll readings) are considered predictors of crop N status for most of the agricultural crops, comprising tomato [30]. In addition, NDVI can be also related to several physiological processes able to influence yield [31]. The highest values of SPAD observed in the OFS, except for the modern genotype “H3402” (Figure 3A), indicated a good photosynthetic rate reached under organic cultivation [32]. A decreasing trend of NDVI albeit not significant was shown from the heirloom to the modern genotypes in both cropping systems (Figure 2B). On the other hand, NDVI was shown to be one of the main parameters involved in the yield gap between OFS and CFS, together with the number of leaves *per* plant, average fruit weight, and nitrogen agronomic efficiency (Figures 1A, 2E, 2C, 5, 6).

The lowest marketable yield gap among the genotypes cultivated in the OFS and in the CFS was obtained by the genotype “BRIGADE”. This was probably determined by its “rustic” behavior (i.e., vigorous and highly productive plants), and due to a similar agronomic performance, both in OFS and CFS, especially in terms of NF (Figure 2D) and HI, which are considered crucial yield components for the crop [33]. Consequently, “BRIGADE” might be considered as an eligible genotype to start specific breeding programs and develop suitable genotypes for the organic cultivation regime.

The highest values of FWP and NAE that resulted in the CFS indicated a maximized use of water and nitrogen compared to the OFS. These results are in agreement with previous studies, confirming the positive correlation between marketable yield and water and nutrient use efficiencies in processing tomato production [17]. On the other hand, genotype “BRIGADE” displayed a similar value of FWP in the two investigated farming systems.

Innovative biofertilizers such as digestate and biochar were proposed as key components in maintaining long-term soil fertility and in order to increase the marketable yield of processing tomato cultivated in the OFS [8]. From this point of view, the combined effort of agronomists and breeders is required to improve the sustainability of the processing tomato cultivated in the OFS.

As far as fruit quality is concerned, an improvement of fruit color and brix *t per* hectare and a decrease of pH were highlighted only in the CFS (going from the heirloom to the modern genotypes), whereas in the OFS, only BY showed an increase associated with the year of release of the assessed genotypes (Figure 4). °Brix is one of the most important fruit quality traits, but it is generally negatively related to yield [34], whereas BY is a trait derived from °Brix and marketable yield [17]. In the OFS, the positive association of genotype “BRIGADE” with high values of BY (Figure 6), once again, drives the attention to this genotype. In fact, “BRIGADE” could be a possible candidate for future breeding programs in order to develop an elite genotype of processing tomatoes suitable for the OFS, reducing the actual gap in term of marketable yield with the CFS. Furthermore, as suggested by Liabeuf and Francis [35] and Ronga et al. [17], °Brix should be considered in the future breeding programs in addition to effort to increase the marketable yield and other fruit quality traits such as color in processing tomatoes.

## 5. Conclusions

Results obtained in the present study displayed that breeding efforts contributed to a significant increase of marketable yield and fruit quality of processing tomato genotypes cultivated in Italy. In particular, going from heirloom to modern genotypes, HI and fruit number *per* plant were the main traits involved to achieve marketable yield gains. Important fruit quality traits such as °Brix yield and color showed significant genetic gains. On the other hand, total yield and °Brix remained unchanged in the modern genotypes and might be considered in future breeding programs to improve both fruit yield and quality. Novel elite genotypes, suitable to be cultivated in the low-input farming systems, could contribute to reduce the current yield gap between OFS and CFS. From this point of view, efforts should be made to increase LAI, fruit number *per* plant, and NAE of the genotypes suitable to be cultivated in the OFS. The effects of different plant densities on fruit yield and quality should be investigated in further studies. Finally, our results should be validated also in other important geographic areas suited for the production of processing tomato.

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