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Morphological, Leaf Nutrient, and Fruit Quality Characteristics of Diverse Tomato Cultivars under Organic Low-Input Management

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Abstract: Increasing fruit yield and quality of tomatoes under organic low-input conditions remains a challenge for producers and breeders. Therefore, it is necessary to identify superior tomato cultivars that are suitable for production and use as parents in breeding programmes. In the present study, the variations in plant morphology and fruit quality characteristics of tomato cultivars were assessed to reveal the traits associated with improved yield and fruit quality. Sixty diverse tomato cultivars were screened in 2015, and in 2016, a subset of 20 cultivars was selected for further evaluation under organic low-input conditions. The results showed high variability among cultivars in all 28 traits that were observed. Salad cultivars had lower plant growth and fruit quality (minerals, dry matter, total soluble solids, and total phenolics) by 10–70%, but they displayed 10–60% higher fruit yield and leaf minerals than cocktail cultivars. Salad tomato cultivars with superior yield and harvest index were mainly derived from breeding for intensive indoor production. Cocktail cultivars with superior yield were mainly derived from organic and outdoor breeding programs. There was a trade-off between fruit yield and quality, indicating a challenge for simultaneous improvement of yield and quality. The importance of Mg was highlighted because of its contribution to the fruit mineral concentration and fruit quality. Cultivars superior in one trait or trait combination under organic low-input conditions were identified to be used by producers and breeders as superior cultivars to meet their production targets and breeding objectives. The importance of Mg provides a novel path for further research on improving soil-available Mg in organic tomato production to enhance fruit mineral concentration and fruit quality in general.

Keywords: cultivar; fruit yield; fruit quality; magnesium; organic low-input management; tomato

1. Introduction

Tomato production and consumption have grown rapidly worldwide over the past 25 years [1]. The tomato fruit is a valuable source of minerals and vitamins necessary in the human diet [2]. At the same time, the demand for organically grown tomatoes has also increased [3], driven by consumer perception that organic food is more sustainable and of better quality than food derived from conventional farming [4]. However, there is a lack of tomato cultivars bred for organic production that are both high-yielding and of superior fruit quality [5]. Tomato cultivars suitable for organic production require an adaptation strategy with more efficient nutrient uptake and utilisation under limited nutrient availability in the soils [6].

The diversity of cultivated tomato has increased as a result of domestication and breeding [7]. Consequently, average fruit weight varies strongly among cultivars, ranging from a few grams to one kilogram [8]. Plant morphological characteristics and fruit quality of these cultivars also differ because cultivars bred for high yield often have poor flavour and nutritional quality [9]. Tomato flavour is derived mainly from sugars, acids, and aromatic volatiles [10]. Small-fruited tomatoes may have better quality attributes but a lower yield than large-fruited tomatoes [11]. There is no universal classification of tomato regarding average fruit weight; however, Scott et al. [9] referred to tomatoes with a high sugar concentration and weighing less than 50 g as cocktail tomatoes. Based on this differentiation and average fruit weight recorded in the present study, we classified tomato cultivars with a weight exceeding 52 g per fruit as salad tomatoes. Consumers' preference for cocktail tomatoes has increased in the last decade. For example, the production of cocktail tomatoes rapidly increased from 7% of the total tomato production in the Netherlands in 2012 to 30% in 2019. In Belgium, cocktail tomato consumption was 40% compared to the total number of purchased tomatoes per household in 2019 [12]. The evaluation of salad and cocktail cultivars under organic low-input management is important for selecting superior cultivars from each fruit type for production and future breeding programmes.

The focus of tomato production, especially in Germany and the Netherlands, is on the fresh market using indeterminate cultivars that continuously produce fruit for an extended time period [13]. This requires a relatively high nutrient availability in the soil to sustain growth and yield. Recently, there has been increasing consumer demand for high-quality fruit in terms of visual appearance and flavour [13,14]. Calcium, magnesium, potassium, and phosphorus are the major minerals that make up about 8% of the dry matter in tomato fruit [15]. The concentration of these fruit minerals influences fruit colour, sweetness, and sourness [16]. Sweetness and sourness are the main determinants of tomato fruit quality [16,17], making the fruit mineral concentration a key factor for consumer acceptance. Therefore, the ability of tomato cultivars to uptake and allocate these nutrients efficiently to leaves and fruit is essential. To date, the effect of tomato cultivars on fruit mineral concentration, especially their relationship with fruit yield and leaf mineral nutrients, has not been extensively studied.

In Germany, commercial tomato production covered an area of 398 hectares in 2018 [1]; about 17% of this area was used for organic cultivation [18]. The high demand for organic tomato relies heavily on imports [19,20]. Therefore, it is necessary to identify superior cultivars suitable for organic low-input production and for future breeding and selection programmes to genetically improve tomato fruit yield and quality. In the present study, in 2015, 60 tomato cultivars released between 1880 and 2015 with a large range of average fruit weight and, in 2016, a subset of 20 cultivars, were assessed under organic low-input conditions. These cultivars were used in the past or are still grown in present tomato production systems. Two very small-fruited cultivars, 'Rote Murmel' and 'Golden Currant' (Table 1), are usually grown as currant tomatoes with multiple shoots; they were included in the study because of their relevance in amateur outdoor production. The objective of this study was to characterise the plant growth, leaf nutrients, and fruit quality of diverse tomato cultivars in organic low-input production. We hypothesised that there is significant variation among tomato cultivars under organic low-input conditions, enabling the identification of cultivars superior for growth, yield, and fruit quality traits. The information is valuable for tomato growers to select suitable cultivars for production under low-input management and for breeders to identity traits and cultivars as potential parents for future breeding programmes. This study presented the first information on superior cultivars suitable for organic low-input production resulting from the evaluation of a diverse set of cultivars. Furthermore, the importance of Mg, which has been neglected under organic production, in improving tomato fruit quality was highlighted.

Table 1. Overview of tomato cultivars assessed in 2015 and 2016.

Cultivar Name Salad Cultivars (>52 g fruit^{-1})	Fruit Colour	Cultivar Name Cocktail Cultivars (<52 g fruit^{-1})	Fruit Colour
Previa F$_1$	Red	**Amoroso F$_1$**	Red
Garance F$_1$	Red	**Annamay F$_1$**	Red
Green Zebra	Green–yellow	Quedlinburger Frühe Liebe	Red
Diplom F$_1$	Red	Ruthje	Red
Cappricia F$_1$	Red	König Humbert	Red
Rougella F$_1$	Red	Clou	Yellow
Sparta F$_1$	Red	**Tastery F$_1$**	Red
Bocati F$_1$	Red	**Primabella**	Red
Phantasia F$_1$	Red	**Sakura F$_1$**	Red
Mecano F$_1$	Red	**Black Cherry**	Red–brown
Hamlet F$_1$	Red	Cerise Gelb	Yellow
Lyterno F$_1$	Red	Yellow Submarine	Yellow
Nordica F$_1$	Red	Zuckertraube	Red
Moneymaker	Red	Dorada	Yellow
Pannovy F$_1$	Red	**Primavera**	Red
Roterno F$_1$	Red	Philovita F$_1$	Red
Hildares F$_1$	Red	Trixi	Red
Bonner Beste	Red	Trilly F$_1$	Red
Tica	Red	**Benarys Gartenfreude**	Red
Ricca	Red	**Bartelly F$_1$**	Red
Aroma	Red	Golden Pearl F$_1$	Yellow
Rheinlands Ruhm	Red	**Resi**	Red
Lukullus	Red	**Supersweet 100 F$_1$**	Red
Goldene Königin	Yellow	**Goldita**	Orange
Harzfeuer F$_1$	Red	Sliwowidnij	Yellow
Auriga	Orange	Rote Murmel	Red
Haubners Vollendung	Red	Golden Currant	Yellow
Dorenia	Red	-	-
Roi Humbert Jaune	Yellow	-	-
Hellfrucht	Red	-	-
Campari F$_1$	Red	-	-
Matina	Red	-	-
Black Plum	Red–brown	-	-

Cultivars shown in bold are the 20 cultivars selected from 2015 for further evaluation in 2016. The cultivars are ordered based on average fruit weight from high to low.

2. Materials and Methods

2.1. Site and Climatic Description

To assess the tomato cultivars, they were grown under low-input conditions in a temperate climate in accordance with certified organic standards [21]. Low-input conditions were defined as receiving no fertiliser application and moderate irrigation. The experiments were carried out at Reinshof Experimental Station, University of Goettingen, at 152 m above sea level on organic fields of Fluventic Eutrochrept soil [22] from May to October in 2015 and 2016. Temperature, relative humidity, and soil properties during the experiments were previously described in Erika et al. [23]. Additionally, available nitrogen concentrations in the soil during the growing period are shown in Table S1 in Supplementary Materials.

2.2. Cultivars

In 2015, 60 indeterminate tomato cultivars were used (Table 1; additional information in Table S2 in Supplementary Materials). They were chosen in close cooperation with extension services, research stations, breeders, seed companies, and the Genebank of the Leibniz Institute of Plant Genetics and Crop Plant Research Gatersleben (IPK, Seeland, Germany). The cultivars covered the entire range from old cultivars released in the 1880s to the most recently developed cultivars. For the traditional cultivars 'Goldene Königin', 'Haubners Vollendung', and 'Rheinlands Ruhm', limited knowledge could be gathered from old books and personal

communications with Arche Noah (Schiltern, Austria) and the Genebank Gatersleben. These cultivars may have been released earlier than stated in Table S2. The years of release of 'Golden Currant', 'Rote Murmel', 'Sliwowidnij', 'Zuckertraube', 'Yellow Submarine', 'Black Cherry', and 'Black Plum' are not known with certainty because—to the best of our knowledge—these were not derived from formal breeding programmes and may have existed long before the year given in Table S2. In the case of 'Goldita', an inbred on-farm selection derived from the original hybrid cultivar was used. 'Aroma' is an advanced breeding line from organic breeder S. Wedemeyer (Kultursaat e.V., Echzell, Germany). A subset of 20 potential cultivars was selected for further evaluation in 2016.

2.3. Experimental Layout and Crop Cultivation

In 2015, the 60 cultivars were assessed in a randomised complete block design with eight blocks and one plant per plot. Two to three tomato seeds were sown in multipot trays QP 96 (Hermann Meyer, Rellingen, Germany) filled with the substrate 'Anzuchtsubstrat Organisch' (Kleeschulte, Rüthen, Germany), and they were reduced to single seedlings after emergence. All seedlings were potted (pot dimension $11 \times 11 \times 11$ cm) 20 days later in the substrate 'Fruhstorfer Bio-Aussaat- und Kräutererde' (Hawita, Vechta, Germany) and maintained in the greenhouse with a temperature of 20 °C during the day and 18 °C during the night. During the first 20 days, the photoperiod was adjusted to 16 h. Seven weeks after germination, the seedlings were transplanted to the field and spaced 50 cm apart within rows, with 100 cm between rows. The growing system was designed to exclude major pathogens to allow the assessment of cultivars without up-to-date field resistance. These pathogens included *Phytophthora infestans* (Mont.) de Bary and *Cladosporium fulvum* (Pers.) Link. Therefore, a well-ventilated rainout shelter with sides open to 1.8 m was used (Figure S1 in Supplementary Materials). Border effects were avoided by planting three border plants at either end of each row. The space between rows was covered with Plantex Gold Unkrautvlies fleece (Hermann Meyer, Rellingen Germany) for weed control. Tomato plants were trellised with strings to vertically support the vine, and the plants were fixed each week. Plants were pruned to the main shoot by removing side shoots on a weekly basis. Drip irrigation was provided through lateral polytube drip lines (John Deere, Moline, IL, USA) with 20 cm emitter spacing. Irrigation was moderate and based on ambient temperature, with a total amount of 150 L m^{-2} applied during the growing season. In 2016, the 20 selected cultivars were further assessed with two plants per plot. The crop cultivation procedures, experimental design, and management practices remained the same as in 2015.

2.4. Sample Collection, Mineral Nutrient, and Quality Determination
2.4.1. Plant Morphology

Plant height was measured at 19 weeks after planting (WAP) in 2015 and at 20 WAP in 2016. The total leaf number of each plant was counted from the first leaf above ground to the last fully developed leaf. Mature tomato fruit was harvested at two-week intervals, starting at 9 WAP in 2015 and 8 WAP in 2016. At each harvest, all mature fruit from each plant was weighed and counted, followed by the calculation of the average fruit weight, total number of tomatoes, and total yield per plant. At 20 WAP in 2015 and 21 WAP in 2016, stem and leaf biomass were determined as fresh weight. The harvest index was then calculated as the fruit yield proportion of total biomass above ground.

2.4.2. Macronutrient Concentrations in Leaves and Fruit

Fully developed leaves in the middle between the apex and soil surface of each plant were sampled at 12 WAP in 2015 and at 13 WAP in 2016 to determine mineral concentrations. Fruits were randomly sampled at 13 WAP in both years to assess quality parameters. The samples were taken at the fully mature stage, as described by Liu et al. [24]. Leaf and fruit samples from the eight field replications were pooled to create four replications for further sample preparation. Leaf samples were oven-dried at 70 °C for 72 h and then ground with a Culatti DFH 48 (Gemini BV, Apeldoorn, the Netherlands) using a 0.5-mm sieve. Ten mature tomatoes per cocktail cultivar and three mature tomatoes per salad cultivar were selected and freeze-dried for four days using an EPSILON 2–40 (Christ, Osterode am Harz, Germany). Fruit samples were then milled with a Mixer Mill MM 400 (Retsch, Haan, Germany) to obtain a homogenous fine powder. The concentrations of phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg), and sulphur (S) in leaf and fruit samples were analysed according to Erika et al. [23]. The ground leaf samples were also used to determine nitrogen (N) and carbon (C) concentrations by dry combustion (Elementar, Langenselbold, Germany).

2.4.3. Fruit Dry Matter (DM), Total Soluble Solids (TSS), and Titratable Acidity (TA)

A subsample of fruit harvested at 13 WAP in 2015 and 2016 was stored at -20 °C for further quality analysis. Ten tomatoes per cocktail cultivar and three per salad cultivar were used for the determination of dry matter, total soluble solids, and titratable acidity in accordance with the procedures described by Kanski et al. [10].

2.4.4. Total Phenolic Concentration (TPC)

The TPC of tomato fruit was determined using a Folin–Ciocalteu assay [25]. A total of 250 mg of the freeze-dried sample was homogenised twice with 5 mL 80% ethanol and centrifuged for 10 min at $5000\times g$. The supernatant from the two steps was pooled and filled, up to 10 mL, with 80% ethanol. For measurement, 500 μL of the extract was suspended with 2.4 mL water, 1 mL 0.5 M NaOH, and 100 μL Folin reagent. The mixture was incubated at 37 °C for 15 min, and absorbance was measured at 736 nm in an HP 8453 UV-Vis spectrophotometer (Hewlett Packard, Böblingen, Germany) against blanks. Finally, the TPC was calculated based on the gallic acid standard calibration curve and expressed as milligrams of gallic acid equivalents per 100 g fresh matter (mg GAE 100 g^{-1} FM).

2.4.5. Fruit Colour

Eight and ten mature tomatoes of cocktail and salad cultivars, respectively, harvested 13 WAP in both years, were measured for fruit colour using a Minolta Chroma meter CR-400 (Konica Minolta Optics, Tokyo, Japan), in accordance with Kanski et al. [10].

2.5. Statistical Analyses

The descriptive statistics of each measured trait were calculated. The effects of cultivar and year were analysed by analysis of variance. Tukey's honestly significant difference (HSD) was calculated at $p < 0.05$ as a post hoc test. Pearson's correlation was employed to investigate trait associations. The calculation and statistical analyses were conducted with Statistix (Version 8.0, Analytical Software, Tallahassee, FL, USA).

3. Results

### 3.1. Variation of 60 Cultivars

Sixty tomato cultivars were grown in 2015 to assess their performance in growth, leaf mineral concentration, yield, and fruit quality under organic low-input management. A total of 28 parameters were investigated. Significant differences among cultivars were observed for all parameters (Table S3 in Supplementary Materials). Plant agronomic traits, such as leaf and stem biomass, fruit yield, average fruit weight, and fruit number, had a high coefficient of variation (CV), ranging from 33.4 to 68.7%. Traits associated with fruit quality characteristics (DM, TSS, TA, and TPC) also obtained medium to high CVs (14.7 to 29.5%). The CVs of other traits related to minerals in leaves and fruit were classified as low to high (1.8 to 27.4%). Fruit colours varied and ranged from light green to red (a*; −11.0 to 27.4) and yellow at different pigment intensities (b*; 9.5 to 45.7) (Table 1 and Table S3). These results indicate a high genetic diversity among the 60 assessed tomato cultivars.

Considering the high diversity of average fruit weight (5.5 to 171.5 g fruit^{-1}), the cultivars were classified, based on average fruit weight, into two groups: salad (>52 g fruit^{-1}) and cocktail (<52 g fruit^{-1}). The results of analysis of variance within the two groups are shown in Table S4 in Supplementary Materials. In salad cultivars, the year of release correlated positively with plant height; fruit yield; harvest index; and leaf C, Ca, and S concentrations (Figure S2 in Supplementary Materials). A high variation of leaf and stem biomass, average fruit weight, and fruit yield enabled the selection of cultivars with superior performance in plant morphology and yield (Figure 1A). Fruit TSS and TA were also included in the selection criteria (Figure 1B) because they were among the most important traits for improving tomato fruit quality to gain consumer acceptance [17]. Presumably, variation in the traits used as selection criteria could be reflected in the variability of other traits on account of trait correlations (Figure S3 in Supplementary Materials). Ultimately, eight salad and twelve cocktail cultivars with outstanding performance in one trait or a combination of traits were selected for further evaluation in 2016 (Figures 1 and 2).

3.2. Morphological and Fruit Quality Characteristics of the 20 Selected Cultivars

The selected 20 cultivars (Table 1; shown in bold) were grown in 2016 to further characterise plant morphology, yield, and fruit quality and to identify the best performing ones for fruit yield and quality in organic low-input management. The dataset for evaluation of these 20 cultivars was obtained from 2015 and 2016. Although cultivars grown in 2016 had lower stem and leaf biomass than those in 2015, the fruit yield of cocktail cultivars in 2016 was 13% higher than that in 2015. Furthermore, an unpaired t-test was used to compare the performance of salad and cocktail cultivars. In both the years, salad cultivars displayed lower plant height, leaf number, leaf and stem biomass, fruit number, fruit mineral concentrations (P, S, Mg, and K), and fruit quality characteristics (DM, TSS, and TPC) by 10–70%, but they had higher fruit yield and leaf mineral concentrations (S, Mg, and Ca) by 10–60% compared to cocktail cultivars (Figure S4 in Supplementary Materials). Because of these differences, the results were analysed separately for each group. For cocktail cultivars, analysis of variance revealed a significant interaction between cultivar and year in plant morphological characteristics and fruit minerals. However, a significant interaction was not clearly observed in salad cultivars (Tables 2 and 3).
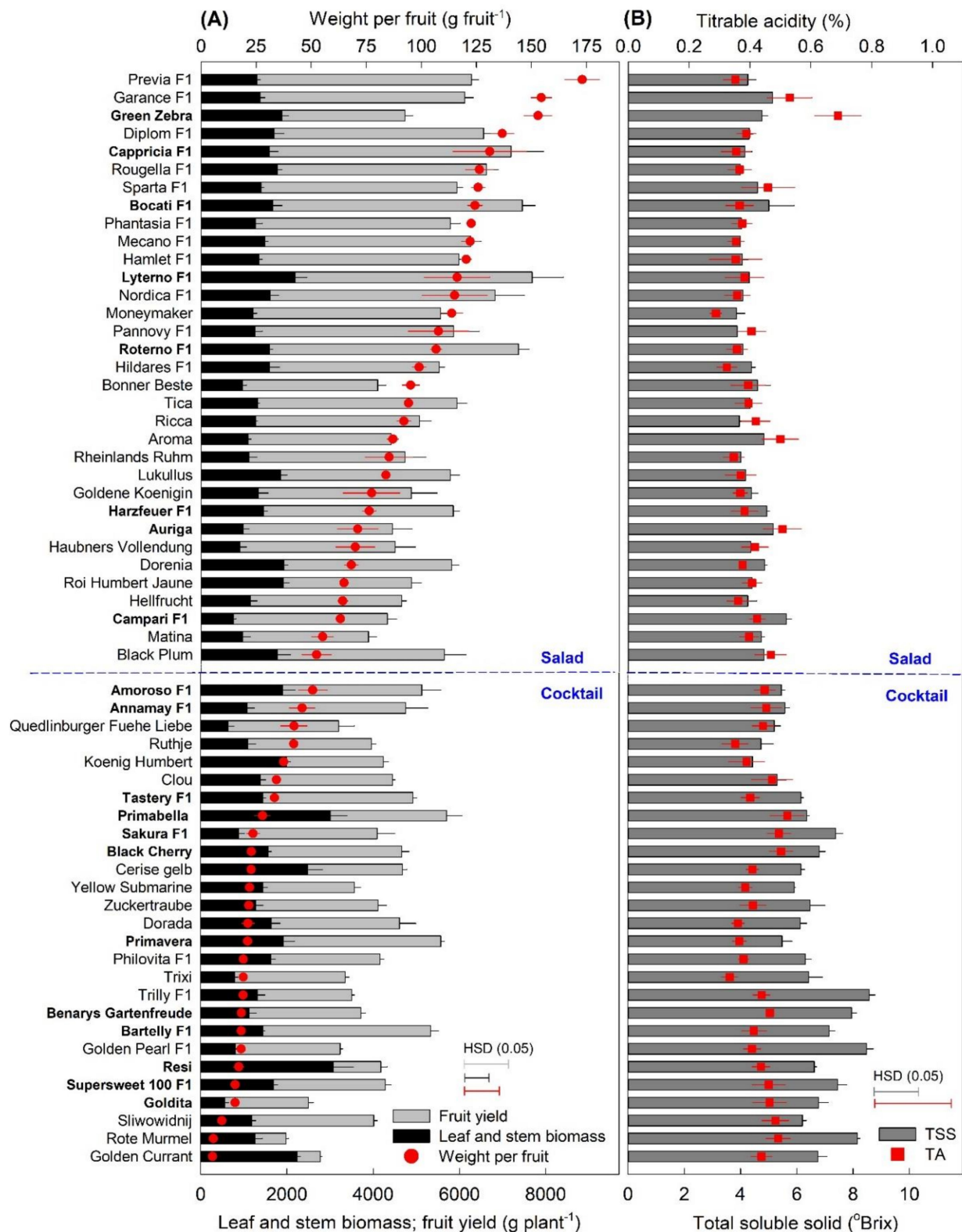
Figure 1. (**A**) Leaf and stem biomass, fruit yield, and average fruit weight and (**B**) fruit total soluble solid (TSS) and titratable acidity (TA) of 60 tomato cultivars grown in 2015. Error bars indicate the standard error of the mean. Cultivars shown in bold are the cultivars selected from 2015 for further evaluation in 2016. Cultivar names 'Goldene Koenigin', 'Quedlinburger Fruehe Liebe', and 'Koenig Humbert' were written as 'Goldene Königin', 'Quedlinburger Frühe Liebe', and 'König Humbert', respectively. The cultivars are ordered based on average fruit weight. Error bars indicate the critical value for comparison of each trait among the 60 cultivars by Tukey's HSD test at *p* < 0.05.

Figure 2. Fruit colour phenotypes of 20 tomato cultivars consisting of eight salad and twelve cocktail cultivars selected in 2015 for further evaluation in 2016 (Photos: L. Chea and J. Lange).

Table 2. Plant morphological and agronomic characteristics of eight salad and twelve cocktail tomato cultivars grown in 2015 and 2016.

Cultivar	PH (cm)	LN (Plant^{-1})	LSB (g Plant^{-1})	FY (g Plant^{-1})	AFW (g Fruit^{-1})	FN (Plant^{-1})	HI	Leaf Minerals (mg g^{-1} DM)						
								C	N	P	K	Mg	Ca	S
Salad cultivar (S)														
Green Zebra	216.3	42	1520	3212	145.7	22	0.76	387.1	28.1	2.0	25.8	5.2	47.8	6.0
Cappricia F$_1$	284.0	49	1321	5724	127.3	45	0.86	382.1	24.4	1.6	22.3	3.3	59.0	7.5
Bocati F$_1$	284.4	47	1408	5680	119.7	48	0.85	384.0	23.9	1.7	21.5	2.9	58.8	6.8
Lyterno F$_1$	308.6	51	1718	5738	115.2	50	0.83	383.7	23.4	1.6	23.5	3.1	56.3	6.3
Roterno F$_1$	283.8	49	1286	5824	105.4	56	0.86	381.8	24.3	1.5	22.4	3.5	56.4	6.8
Harzfeuer F$_1$	231.8	46	1258	4031	74.1	54	0.81	391.0	22.2	1.4	17.8	3.5	47.6	5.4
Auriga	223.6	45	865	3498	73.8	48	0.85	384.4	24.9	1.7	19.2	4.2	56.8	6.6
Campari F$_1$	248.3	45	707	3733	62.8	59	0.87	386.1	23.4	1.6	19.8	3.3	57.1	6.7
CV (%)	13.2	5.8	26.2	24.7	28.8	23.7	4.3	0.8	7.2	11.1	11.9	8.4	20.6	9.7
Significance	***	***	***	***	***	***	***	ns	***	***	***	***	***	**
HSD (0.05)	21.6	4	245	568	9.8	5	0.03	10.4	3.1	0.2	2.7	0.8	7.9	1.4
Years (Y)														
2015	266.9	36	1498	4611	105.2	47	0.82	387.2	23.5	1.7	26.1	3.7	52.3	6.1
2016	254.7	52	1034	4732	100.8	49	0.85	382.8	25.2	1.6	17.0	3.6	57.7	6.9
Significance	**	***	***	ns	**	*	***	*	**	***	***	ns	**	***
Interaction (SxY)	**	*	***	ns	ns	*	**	ns	ns	**	ns	*	ns	ns
Cocktail cultivar (C)														
Amoroso F$_1$	266.9	49	1651	3539	49.3	73	0.77	393.1	23.6	1.6	21.6	3.5	47.9	5.5
Annamay F$_1$	303.5	53	974	3902	47.1	83	0.84	383.3	21.9	1.6	21.6	3.5	59.5	6.6
Tastery F$_1$	307.8	51	1289	3598	33.0	110	0.79	394.7	26.5	1.7	25.2	3.2	48.9	6.5
Primabella	320.0	62	2583	3088	27.9	111	0.62	402.9	24.8	1.9	24.7	3.1	39.4	4.5
Sakura F$_1$	299.8	56	822	3368	23.9	141	0.84	384.0	23.0	1.5	19.6	3.3	63.2	6.0
Black Cherry	325.9	49	1394	3162	24.1	133	0.76	394.4	26.2	1.7	18.9	4.4	51.6	5.2
Primavera	336.4	59	1655	3838	21.4	181	0.74	386.8	24.6	1.7	26.5	3.0	53.4	5.3
Benarys Gartenfreude	256.1	48	1048	2816	18.8	150	0.78	382.7	21.0	1.5	17.4	2.9	61.7	5.2
Bartelly F$_1$	321.6	53	1295	4076	16.6	252	0.81	386.5	25.8	1.7	25.1	4.2	58.3	6.0
Resi	346.0	59	2578	1186	18.6	64	0.37	398.1	25.0	1.8	21.5	4.2	40.9	5.2
Supersweet 100 F$_1$	332.8	58	1593	2905	14.7	202	0.71	392.1	23.7	1.6	23.8	3.1	47.9	5.2
Goldita	225.6	53	563	2115	16.3	129	0.83	401.2	23.7	1.4	21.2	3.1	46.8	4.5
CV (%)	12.0	8.4	42.9	26.2	44.8	40.7	17.8	1.8	6.9	8.7	12.6	15.1	14.8	12.5
Significance	***	***	***	***	***	***	***	***	***	***	***	***	***	***
HSD (0.05)	30.1	5	417	485	2.9	25	0.05	8.5	3.2	0.2	4.1	0.7	7.9	1.1
Years (Y)														
2015	297.8	42	1621	2938	25.6	127	0.72	387.0	23.6	1.7	26.4	3.9	55.2	5.6
2016	308.9	60	1287	3323	25.9	146	0.76	396.3	24.8	1.6	18.1	3.0	48.1	5.3
Significance	**	***	***	***	ns	***	***	***	***	***	***	***	***	*
Interaction (CxY)	***	***	***	***	***	***	***	ns	***	ns	*	ns	ns	ns

PH = plant height; LN = leaf number; LSB = leaf and stem biomass; FY = fruit yield; AFW = average fruit weight, FN = fruit number; HI = harvest index; DM = dry matter; CV = coefficient of variation; ns indicates a nonsignificant difference; *, ** and *** indicate significance differences of each factor and interaction at $p < 0.05$, $p < 0.01$ and $p < 0.001$, respectively; HSD(0.05) = critical value for comparisons by Tukey's honestly significant difference (HSD) test at $p < 0.05$. The cultivars are ordered based on average fruit weight.

Table 3. Fruit quality characteristics of eight salad and twelve cocktail cultivars grown in 2015 and 2016.

Cultivar	Fruit Minerals (mg 100 g^{-1} FW)					DM (%)	TSS (°Brix)	TA (%)	TPC (mg GAE 100 g^{-1}) FW)	Fruit Colour				
	P [#]	K [#]	Mg [#]	Ca [#]	S					L *	a *	b *	C *	°h
Salad cultivar (S)														
Green Zebra	30.7	297.4	14.2	13.2	15.6	5.7	5.1	0.65	139.2	58.9	−10.7	37.0	41.9	105.4
Cappricia F$_1$	25.9	246.9	8.5	15.3	13.0	5.6	4.6	0.35	109.0	53.4	22.5	28.4	39.6	54.0
Bocati F$_1$	21.4	212.4	8.3	12.4	11.0	5.2	5.1	0.38	105.2	53.1	24.4	28.0	40.1	51.2
Lyterno F$_1$	26.2	243.7	9.2	15.2	13.5	5.9	4.6	0.38	131.8	52.8	20.0	25.6	35.8	54.4
Roterno F$_1$	24.4	237.9	9.4	14.5	13.2	5.5	4.5	0.37	119.3	53.3	21.6	27.8	38.3	54.4
Harzfeuer F$_1$	26.8	303.2	10.9	11.7	14.4	6.8	5.5	0.42	143.4	50.4	19.5	23.8	34.1	53.4
Auriga	29.0	299.0	13.5	8.0	14.7	6.9	5.5	0.53	160.8	61.5	13.5	42.8	47.5	73.1
Campari F$_1$	30.1	293.9	11.9	13.7	15.0	6.9	6.1	0.47	158.1	50.2	17.0	23.1	31.9	56.4
CV (%)	11.6	13.3	18.5	21.2	10.6	11.6	10.6	23.4	15.7	7.3	70.6	23.2	12.6	29.5
Significance	***	***	***	***	***	***	***	***	***	***	***	***	***	***
HSD (0.05)	5.8	56.5	2.2	4.6	2.8	1.1	1.0	0.08	21.7	1.9	2.0	2.8	3.3	6.4
Years (Y)														
2015	28.7	280.1	10.6	13.2	14.9	5.8	4.7	0.43	177.0	54.1	18.2	30.4	37.1	58.8
2016	25.0	254.1	10.9	12.8	12.8	6.3	5.5	0.46	93.0	54.2	14.5	28.6	39.9	65.5
Significance	***	**	ns	ns	***	*	***	ns	***	ns	***	**	ns	**
Interaction (SxY)	ns	ns	ns	**	ns	ns	ns	ns	ns	ns	ns	ns	ns	ns
Cocktail cultivar (C)														
Amoroso F$_1$	27.8	233.8	9.8	12.9	13.9	7.4	6.0	0.49	151.7	49.6	13.3	20.4	27.9	59.6
Annamay F$_1$	31.3	314.2	13.4	15.0	15.4	7.1	6.2	0.50	176.8	50.8	17.3	22.7	32.0	54.9
Tastery F$_1$	31.5	266.9	11.6	13.7	15.1	8.3	6.7	0.39	167.8	51.4	13.1	23.1	30.1	62.5
Primabella	38.5	339.3	14.4	13.4	19.1	8.3	6.8	0.54	203.1	50.4	19.9	23.1	33.7	51.6
Sakura F$_1$	31.3	297.6	12.9	12.4	14.6	9.0	7.7	0.53	200.7	49.3	13.2	21.3	28.5	60.1
Black Cherry	27.4	253.8	11.6	11.9	14.9	7.6	6.9	0.53	172.2	47.9	4.8	9.8	16.1	66.5
Primavera	30.5	273.2	10.6	13.1	16.4	7.4	6.2	0.38	188.4	49.6	12.5	21.0	28.2	61.5
Benarys Gartenfreude	36.6	334.3	12.8	9.6	18.0	10.4	8.3	0.55	177.6	50.0	13.9	20.5	28.5	58.6
Bartelly F1	39.0	320.9	13.5	16.9	18.8	8.5	7.7	0.45	211.8	49.9	14.0	20.2	28.2	57.6
Resi	48.2	360.6	16.6	19.4	21.7	8.0	6.9	0.47	205.4	50.5	18.5	20.9	31.6	51.0
Supersweet 100 F$_1$	42.7	344.8	15.5	9.7	19.9	10.1	8.2	0.54	224.2	49.7	15.9	21.4	30.1	55.7
Goldita	33.6	310.6	13.2	17.7	20.1	9.5	7.4	0.51	275.6	56.2	7.0	31.3	35.5	78.3
CV (%)	18.1	13.0	21.7	14.9	15.0	12.7	10.9	11.6	16.6	4.0	31.7	22.0	16.4	12.2
Significance	***	***	***	***	***	***	***	***	***	***	***	***	***	***
HSD (0.05)	8.4	70.7	3.3	5.4	4.6	1.7	0.6	0.08	33.0	1.2	2.6	2.3	3.4	5.9
Years (Y)														
2015	35.0	297.5	12.2	14.3	17.5	8.3	6.6	0.45	250.3	50.2	14.5	22.0	26.8	56.3
2016	34.7	310.9	13.8	13.4	17.2	8.7	7.6	0.53	142.3	50.7	12.7	20.6	31.6	63.4
Significance	ns	***	***	ns	ns	ns	***	***	***	**	***	***	*	***
Interaction (CxY)	*	**	**	*	*	ns	ns	ns	**	***	***	***	ns	ns

DM = dry matter; TSS = total soluble solid; TA = titratable acidity; TPC = total phenolic concentration; GAE = gallic acid equivalent; FW = fresh weight; CV = coefficient of variation; ns indicates a nonsignificant difference; *, ** and *** indicate a significance difference of each factor and interaction at $p < 0.05$ $p < 0.01$, and $p < 0.001$ respectively; HSD (0.05) = critical value for comparisons by Tukey's honestly significant difference (HSD) test at $p < 0.05$; [#] data taken from Erika et al. [23]. The cultivars are ordered based on average fruit weight.

3.2.1. Plant Morphological Characteristics

Plant height, leaf number, leaf and stem biomass, fruit yield, average fruit weight, fruit number, and harvest index differed significantly within salad and cocktail cultivars (Table 2). In salad cultivars, plant height, leaf number, and leaf and stem biomass reached 308.6 cm, 51 plant^{-1}, and 1718 g plant^{-1}, respectively, in 'Lyterno F$_1$'. However, 'Roterno F$_1$' displayed the highest fruit yield (5824 g plant^{-1}) and a high harvest index (0.86). In cocktail cultivars, the tallest plant height (346.0 cm) was observed in 'Resi', and the highest leaf number (62 plant^{-1}) and leaf and stem biomass (2583 g plant^{-1}) were detected in 'Primabella'. 'Bartelly F$_1$' had the highest fruit yield (4076 g plant^{-1}) and fruit number (252 plant^{-1}). 'Sakura F$_1$' and 'Annamay F$_1$' obtained the highest harvest index (0.84). These results suggested that in both salad and cocktail cultivars, improved plant growth did not guarantee higher fruit yield.

3.2.2. Leaf Macronutrient Concentration

Mineral analyses in leaves showed that the salad cultivars with superior growth and fruit yield mentioned above had leaf macronutrient concentrations within average ranges (Table 2). Nevertheless, leaves of 'Green Zebra' contained the highest N, P, K, and Mg concentrations, which were 28.1, 2.0, 25.8, and 5.2 mg g^{-1}, respectively. The highest leaf Ca and S concentrations were observed in 'Cappricia F$_1$'. Among cocktail cultivars, 'Resi', which had the highest leaf and stem biomass, showed leaf concentrations of 398.1, 25.0, 1.8, and 4.2 mg g^{-1} for C, N, P, and Mg, respectively, which were not significantly different from the highest values (Table 2). Moreover, leaf N, P, K, Ca, Mg, and S of

the cultivar with the highest fruit yield ('Bartelly F_1') were 25.8, 1.7, 25.1, 4.2, 58.3, and 6.0 mg g^{-1}, respectively, and not significantly different from the highest values. Therefore, leaf macronutrient concentration could contribute to enhanced plant biomass and fruit yield of cocktail cultivars, but this trend was not evident in salad cultivars.

3.2.3. Fruit Minerals

As minerals are essential for consumers' health, fruit macronutrient concentrations were also characterised. Mineral concentrations in the fruit of salad and cocktail cultivars were highly variable, in which their CVs ranged from 10.6 to 21.2% and 13.0 to 21.7%, respectively (Table 3). The relationships between leaf and fruit minerals were further determined by Pearson's correlation analysis. We found a significant correlation between leaf and fruit Mg within salad cultivars (Figure 3A). 'Auriga' and 'Green Zebra' were outstanding cultivars for Mg concentration in both leaves and fruit. In cocktail cultivars, 'Resi' had relatively high Mg concentration in fruits and leaves (Figure 3A). No other significant correlation between leaf and fruit minerals was detected.
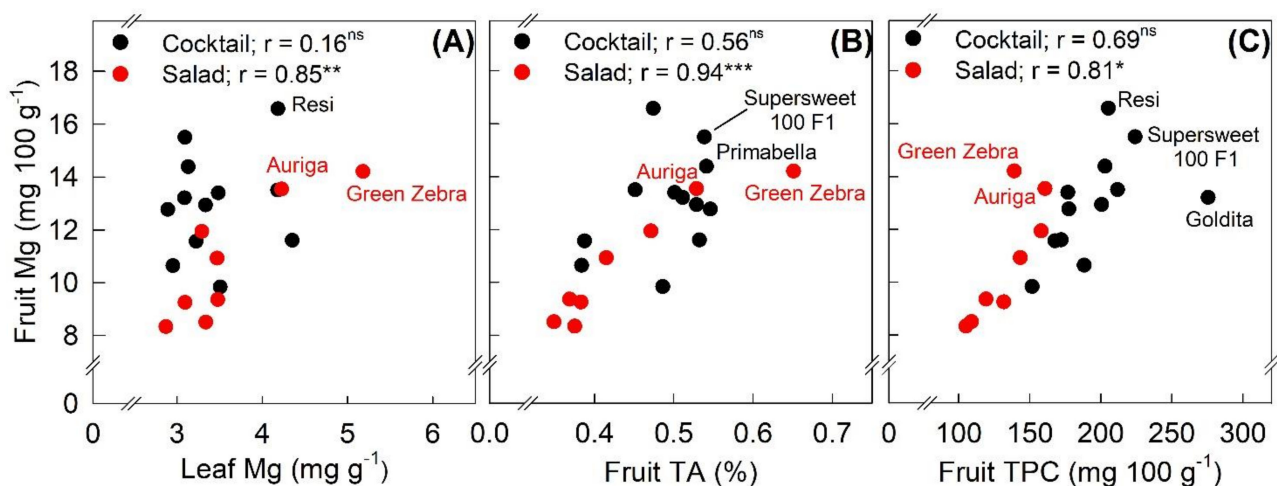
Figure 3. Relationship between fruit magnesium (Mg) and (**A**) leaf Mg, (**B**) fruit titratable acidity (TA), and (**C**) fruit total phenolic concentration (TPC) of salad ($n = 8$) and cocktail ($n = 12$) cultivars grown in 2015 and 2016. ns, *, ** and *** indicate a nonsignificant and significant correlation at $p < 0.05$, $p < 0.01$ and $p < 0.001$ respectively. Cultivars mentioned in the figures are cultivars with promising performance in trait combinations.

3.2.4. Fruit Quality Characteristics and Fruit Colour

The fruit DM, TSS, TA, TPC, and colour of salad and cocktail cultivars were measured because they are important parameters that determine tomato fruit quality and consumer acceptance. High variability was observed for each trait; the CVs ranged from 7.3 to 70.6% and 4.0 to 31.7% in salad and cocktail cultivars, respectively. Within salad cultivars, 'Auriga' and 'Campari F_1' had the highest fruit DM (6.9%), and the fruit of both cultivars also contained a relatively high TSS (5.5 and 6.1 °Brix, respectively) and TPC (160.8 and 158.1 mg GAE 100 g^{-1}, respectively). The highest TA (0.65%) was measured in 'Green Zebra'. In cocktail cultivars, 'Benarys Gartenfreude' yielded the highest DM, TSS, and TA (10.4%, 8.3 °Brix, and 0.55%, respectively). The highest TPC (275.6 mg GAE 100 g^{-1}) was detected in the fruit of 'Goldita'. The fruit colour was less variable because the fruit of most cultivars was red (a* > 10), except salad cultivar 'Green Zebra' and cocktail cultivar 'Black Cherry' (Figure 2, Table 3). In addition to the abovementioned positive correlation between fruit and leaf Mg, a positive correlation was also found between fruit Mg and TA (Figure 3B) and TPC (Figure 3C) in salad cultivars. Even though we could not observe these significant relationships in cocktail cultivars, 'Supersweet 100 F_1', 'Primabella', 'Resi', and 'Goldita' were identified as superior cultivars in the trait combinations of fruit Mg,

TSS, and TPC. These cultivars had the potential for improved fruit quality under organic low-input management.

3.2.5. Correlation between Fruit Yield and Quality

The correlation between fruit yield and quality was analysed to determine whether the variations in fruit quality characteristics were associated with yield and fruit minerals. Pearson's correlation analysis revealed that fruit yield was negatively correlated with fruit minerals (P, K, Mg, and S) and quality characteristics (TSS, TA, and TPC) in salad cultivars (Figure 4A). In cocktail cultivars, significantly negative relationships were observed only between fruit yield and fruit P, Mg, and S (Figure 4B). These results imply a trade-off between fruit yield and quality at different magnitudes. In both salad and cocktail cultivars, a positive correlation was identified among fruit mineral concentrations (P, K, Mg, and S), suggesting synergistic effects of mineral allocation in fruit.
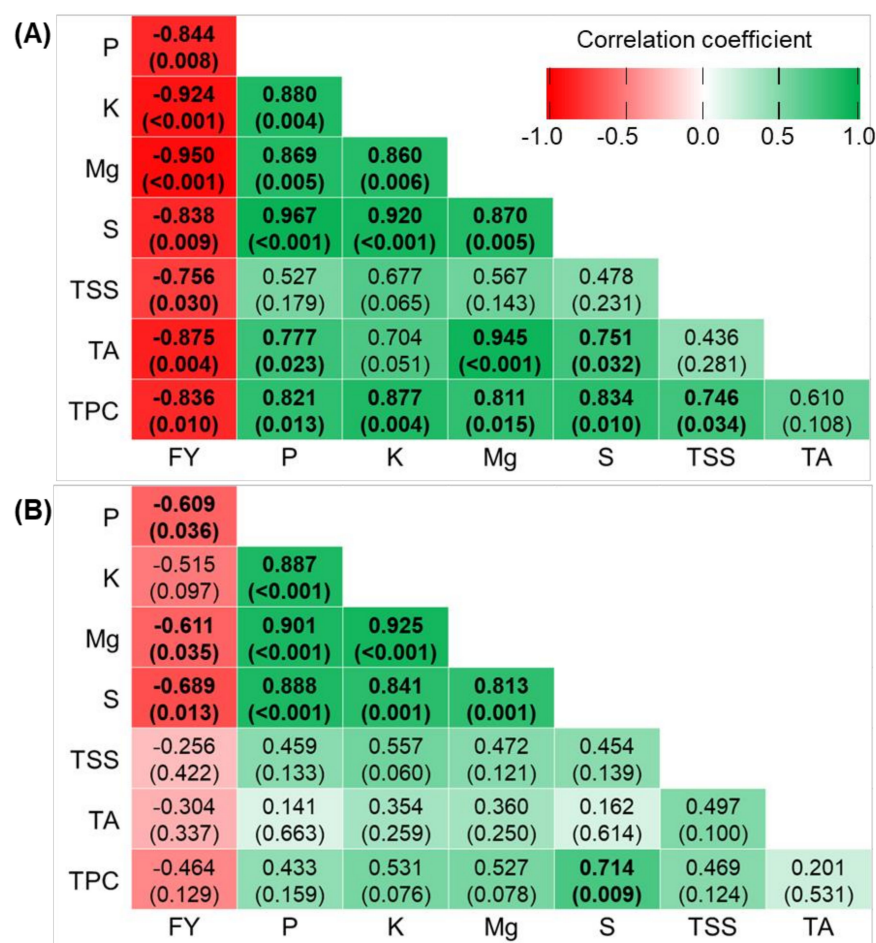
Figure 4. Pearson's correlation coefficient and *p*-values (in parentheses) among fruit quality traits of salad ((**A**), *n* = 8) and cocktail ((**B**), *n* = 12) tomato cultivars in 2015 and 2016. Values in bold are significant at *p* < 0.05. FY = fruit yield; P = phosphorus; K = potassium; Mg = magnesium; S = sulphur; TSS = total soluble solid; TA = titratable acidity; TPC = total phenolic concentration.

4. Discussion

The growing system used in our study can be characterised as a well-ventilated indoor or covered outdoor. The use of a rainout shelter successfully limited the presence of major pathogens that restrict indoor and outdoor tomato production. Even though it is well-known that tomato fruit provides numerous health benefits for humans, there is a lack of breeding programmes for nutritional quality traits of the tomato [26]. Information on genotypic variation in plant morphology and fruit quality is important for producers and

breeders to identify cultivars for production and resources in breeding programmes for improved yield and fruit quality under organic low-input management. In the present study, a diverse set of 60 tomato cultivars was first screened in 2015, and then a subset of 20 potential cultivars in plant morphology, agronomic, and fruit quality traits were selected for further evaluation in 2016. The organic low-input conditions in the present study were similar to the description of Fess et al. [27]. From the results of a two-year evaluation of these 20 cultivars, cultivars superior for fruit yield and quality traits were finally identified.

4.1. Genotypic Variability of 60 Tomato Cultivars

Morphological and biochemical approaches were employed to characterise 60 cultivars under organic low-input management. The variations of 28 traits were similar to or higher than those found in previous studies that tested tomato cultivars in organic outdoor conditions [28], conventional plastic greenhouses [26], and conventional outdoor conditions [29]. The lower variation of some traits reported in these studies could have been caused by a smaller number of cultivars used in the trials. In addition to these reports, this study provided the first evidence of tomato panels consisting of very diverse average fruit weight, fruit numbers per plant, and leaf and stem biomass under rainout shelters in organic low-input conditions (Table 1 and Table S3). These traits are considered the main drivers for fruit yield variation in tomato [29,30]. The harvest index of the cultivars in our study (0.37 to 0.87) exceeded the range reported by Jones [31]. The wide range of variation in these traits determined the final use of these cultivars. Since average fruit weight plays an important role in determining fruit yield and quality [30], it was necessary to separately characterise the tomato cultivars into salad and cocktail groups in our study. The positive correlation between year of release with fruit yield, harvest index, and leaf mineral concentration of salad cultivars indicated that breeding for yield improvement in large-fruited tomato has been successful. Similar to our findings, Barrios-Masias and Jackson [29] and Higashide and Heuvelink [32] also reported a significant increase in fruit yield of tomato cultivars released over the last 50 years, which could be caused by enhanced fruit set, harvest index, and leaf photosynthetic capacity. Superior cultivars were derived from very different breeding backgrounds (Table S2). Salad tomato cultivars with superior performance, particularly yield and harvest index, were mainly derived from recent breeding for intensive indoor production. High-yielding cocktail cultivars were mainly derived from organic and outdoor breeding programmes. Many of the cultivars, such as 'Primabella', 'Primavera', and 'Resi', that stand out with important traits for organic low-input production were selected in organic outdoor breeding programmes. Details about the breeding background are shown in Table S2. This emphasises the importance of selection in conditions with suboptimal climates and limited nutrient supply. From producer and consumer perspectives, 20 cultivars were selected for further evaluation in 2016. The selection was on leaf and stem biomass, fruit yield, TSS, and TA, in which two to five superior cultivars in each trait were selected.

4.2. Morphological and Fruit Quality Characterisation of the 20 Selected Cultivars

In both years of evaluation, salad cultivars had better performance in growth and fruit yield, but their fruit quality was lower than that of cocktail cultivars (Figure S4). Similar trends were also observed by Zörb et al. [28], who evaluated 24 tomato cultivars and breeding lines under outdoor conditions. The higher leaf and stem biomass of cocktail compared with salad cultivars was caused by its greater plant height and leaf number [33]. Salad cultivars have been mainly bred for improved fruit yield and harvest index [29,34]. The absorbed mineral nutrients of these cultivars are allocated to the leaves for photosynthesis and to the fruit for yield formation. Nevertheless, fruit mineral concentrations and values of other quality characteristics are lower in salad cultivars than in cocktail cultivars, which could be caused by a dilution effect or lower mineral uptake. Such effects commonly occur when selective breeding successfully increases crop yield [35]. Moreover, fruit quality traits might be considered less important in breeding for salad cultivars compared to cocktail

cultivars [28,34]. Consumer preference for cocktail tomatoes has increased because of their attractive visual appearance and enhanced taste and aroma [13,36].

Considering genotypic differences between salad and cocktail cultivars, high variations in plant growth and fruit quality characteristics were also observed in both years of evaluation (Tables 2 and 3). These variations provided the opportunity to further select cultivars with superior yield and fruit quality. Our results imply that improved growth does not necessarily result in higher fruit yield, but leaf mineral concentration remains an important factor because it is an indicator of plant nutritional status [37,38]. Average fruit weight is an important determinant of fruit yield. Fruit yield can be enhanced by increasing the average fruit weight, but the trade-off between average fruit weight and fruit number per plant should be minimised [29]. In organic farming, N and P are considered limiting nutrients for plants [5,39]. However, if we accept the optimal leaf N:P ratio to be between 14:1 and 16:1 [40], the plant growth of many cultivars was not restricted in our study by the availability of these mineral nutrients in the soil, although the soil N concentration was lower in 2016 compared to 2015 in the early growing season (Table S1). This low soil N in 2016 may have reduced—but not limited—leaf and stem biomass (Table 2). Nevertheless, the fruit yield of salad cultivars was less affected, while the fruit yield of cocktail cultivars was higher in 2016 than in 2015. The difference in fruit yield of cocktail cultivars in both years may be caused by plant adaptation to modulate dry matter allocation to fruit. Additionally, 'Green Zebra', 'Tastery F1', and 'Primabella' had relatively high leaf N and P concentrations (Table 2). Potential N and P uptake by these cultivars may be enhanced by better root architecture and its response to mycorrhizal and plant growth-promoting rhizobacteria associations [41,42], which become important with inadequate N and P availability in the soil.

It remains questionable whether high mineral concentrations in leaves also contribute to enhanced mineral concentrations in fruit. Therefore, a correlation analysis of minerals in leaves and fruit was conducted. Interestingly, the results showed that salad cultivars with high Mg in leaves also contained high Mg in fruit. Moreover, fruit Mg also positively correlated with fruit TA and TPC (Figure 3). These findings highlight the importance of Mg in improving tomato fruit quality, which has thus far been underestimated in organic low-input conditions. In recent decades, greater emphasis has been placed on the balance of N, P, and K for improved crop production in organic farming because of the high rates of export from the farm, but their availabilities in the soil are frequently relatively low [43]. However, there are only a few studies on the improvement of soil-exchangeable Mg in organic crop production. From a broader point of view, Mg plays an important role in photosynthesis and the transport of photoassimilates from source to sink organs [44]. Wang et al. [45] reported that sufficient Mg supply increased leaf Mg by 34.4% and vegetable yield by 8.9%, indicating that Mg is an efficient nutrient to improve crop yield compared to the application of other nutrients. Kashinath et al. [46] found a tomato yield increase from 7.7 to 17.9 t ha^{-1} because of optimum Mg application under conventional production. With respect to food quality, the Mg concentration in vegetables has significantly declined over the past 50 years [47]. Dietary Mg deficiency poses a major problem in the world [48] and has been associated with cardiovascular diseases [47]. High Mg concentration in tomato fruit also contributes to enhanced Mg intake for consumers. Positive correlations were also observed between fruit Mg and fruit P, K, and S in both cocktail and salad cultivars (Figure 4), suggesting that increased accumulation of Mg also results in high P, K, and S in fruit due to the balance of these minerals in the soil [49,50]. The positive relationship between fruit Mg with TA and TPC indicates the contribution of Mg towards enhancing the flavour and nutritional quality of tomato fruit. This contribution could be explained by improved carbohydrate transport from leaves to fruit, which is facilitated by Mg nutrition [48,51]. Promising cultivars for one or a combination of leaf Mg, fruit Mg, TA, and TPC traits are the salad cultivars 'Auriga', 'Green Zebra', and 'Supersweet 100 F$_1$', as well as the cocktail cultivars 'Primabella', 'Resi', and 'Goldita'.

4.3. Trade-Offs between Yield and Fruit Quality

Negative correlations were observed between fruit yield and quality traits in salad and cocktail cultivars (Figure 4). The results implied a trade-off between achieving a high yield and improved fruit quality. Similar tendencies were also observed by Zörb et al. [28]. The negative correlations were stronger in salad than in cocktail cultivars, suggesting possibilities for improvement of fruit yield and quality in cocktail cultivars. The same task is very challenging in salad cultivars. Despite that there has been little improvement in the quality of salad cultivars, greater emphasis is at present being placed on improving these traits, e.g., sugar concentration, due to a growing awareness that taste and flavour are determinant aspects of tomato marketability [52]. Cocktail cultivars are usually consumed fresh; therefore, fruit quality traits, such as TSS and TA, have become important. This information is crucial for producers, enabling the selection of suitable cultivars (Table 4) based on marketing targets. For breeders, there is potential to cross salad and cocktail cultivars based on breeding objectives [28]. Therefore, the characterisation of salad and cocktail cultivars provides an outlook for organic breeding programmes for improved tomato yield and fruit quality.

Table 4. Cultivars with one or more superior traits under organic low-input management.

Cultivar	LSB	Fruit Yield	Leaf N	Leaf P	Leaf Mg	Fruit Mg	Fruit TSS	Fruit TA	Fruit TPC
Salad cultivars									
Lyterno F_1	X								
Green Zebra			X	X	X	X	X	X	
Roterno F_1		X							
Auriga F_1					X	X	X	X	X
Campari F_1									X
Cocktail cultivars									
Tastery F_1			X	X					
Primabella			X	X	X	X	X	X	
Bartelly F_1		X							
Resi	X				X	X	X	X	
Supersweet 100 F_1					X	X	X	X	
Goldita					X	X	X	X	X

X indicates the trait of the cultivars, based on the data in Tables 2 and 3; LSB = leaf and stem biomass; TSS = total soluble solid; TA = titratable acidity; TPC = total phenolic concentration.

5. Conclusions

Our study revealed high genotypic variability in the plant morphology and fruit quality of 60 tomato cultivars in organic low-input management. A subset of 20 cultivars was selected for further characterisation and selection of superior cultivars, which are summarised in Table 4. The different response patterns of salad and cocktail cultivars provide an outlook on improving fruit yield and quality in each group. According to this study, organic breeding has been successful for cocktail tomatoes but only to a limited extent for salad tomatoes. As an adaptation to the changed production systems, plant height, yield, and harvest index of salad tomato cultivars increased with the year of release (1880–2015). It is still a challenge to simultaneously improve fruit yield and quality in tomatoes of both groups. However, the information provided here is useful for producers and breeders to select superior cultivars to meet production targets and breeding objectives. Our focus on the importance of Mg highlights a novel path for further research on improving soil-available Mg in organic tomato production to enhance fruit mineral concentration and quality in general.

ance (ANOVA) of cocktail and salad cultivars and mean comparison between these two groups of cultivars; Figure S1. Organic low-input tomato production under a rainout shelter; Figure S2. Performance of 33 salad tomato cultivars in organic low-input production in 2015. Pearson correlations between year of cultivar release with (A) plant height, (B) leaf C, (C) leaf Ca, (D) leaf S, (E) fruit yield, and (F) harvest index; Figure S3: Correlation among plant morphology and fruit quality traits of salad (*n* = 33, lower diagonal) and cocktail (*n* = 27, upper diagonal) tomato cultivars; Figure S4. Summary of plant morphological characteristics and fruit quality of salad (*n* = 8) and cocktail (*n* = 12) cultivars grown in 2015 and 2016.

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