Variation of morphological descriptors for the evaluation of tomato germplasm and their stability across different growing conditions

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ABSTRACT

Germplasm and breeding materials are usually characterized using morphological and agronomic descriptors, which should have a high heritability. Despite the widespread use of tomato (*Solanum lycopersicum*) standardized descriptors, little information exists on environmental effects on descriptor values and their heritability. We have evaluated 12 tomato accessions from seven cultivar groups in three different environments (open-field conventional, open-field organic, and greenhouse) and characterized them with 36 descriptors. A wide range of variation was found for most descriptors, demonstrating their utility for describing tomato materials and their diversity and relationships. The analysis of descriptors variation reveals that while for some descriptors with a simple genetic control the accession effect accounts for 100% of the variation, for others like yield per plant only 10.83% of the variation observed is due to the accession effect. Although significant differences were found among environments for most descriptors, including a much higher yield in the open-field conventional environment than in the two others, the environmental effect was low for most traits. However, the genotype × environment effect generally had an important contribution to the structure of variation for many descriptors, and for three traits it had the highest contribution to the percentage of the sum of squares. As a result of the variation structure, the heritability values are high (>0.7) for only 10 descriptors, while for five is low (<0.3). Principal components analysis (PCA) reveals that projections in the PCA graph of a same accession grown in different environments plot together in the same area of the PCA graph. Although cultivar groups are generally clearly separated in the PCA graph,

accessions from the same cultivar group in some cases are intermixed. These results have important implications for detecting tomato duplicates and establishing core collections, as well as for analyzing germplasm and breeding results, when using data sets containing data of accessions grown in different environments.

***Keywords**:*
Characterization
Descriptors
Genotype × environment interaction
Germplasm
Heritability
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1. Introduction

Standardized descriptor lists for the characterization of germplasm collections and breeding stocks constitute an important tool for germplasm banks and breeders as they allow using an internationally agreed format, facilitating comparison of characterization data sets among germplasm banks and trials (Gotor et al., 2008). Up to now, Bioversity International has published descriptors lists for over 100 crops (Bioversity International, 2017). Also, the UPOV has descriptors lists for the characterization of new varieties in distinctness, uniformity and stability (DUS) tests (UPOV, 2017). The characterization and evaluation descriptors lists include morphological and agronomic traits that are of relevance for breeders. Depending on the trait, descriptors are metric, meristic, measured according to an arbitrary quantitative scale, or assigned to qualitative states (Grum and Atieno, 2007). Ideally, standardized descriptors should display a wide variation in the collections of materials characterized, as well as having a high heritability (Ortiz Ríos, 2015), which in turn requires a low environmental influence. Descriptors having these characteristics are highly informative. However many traits that are of interest for breeders, in particular those polygenic, are influenced by the environment (Annicchiarico, 2002). For example, yield is a typical example of an important trait highly affected by the environment (van Bueren et al., 2011; van Ittersum et al., 2013). A way to overcome the influence of the

environment is using common controls in the trials, so that an estimate of the environment effect can be obtained allowing its removal in the comparisons of data sets from different environments (Ortíz Ríos, 2015). However, when important genotype × environment exists, the comparisons of distinct materials grown in different environments are flawed, and this can lead to unreliable results (Annichiarico, 2002). High genotype × environment interaction also represents a challenge for the morphological traits-based detection of duplicates in germplasm banks (Diederichsen, 2009).

Tomato (*Solanum lycopersicum* L.) is the most important vegetable crop, and over 75,000 accessions being conserved in germplasm banks (Robertson and Labate, 2006). Bioversity International standardized descriptors have been available for tomato for over two decades (IPGRI, 1996). Since then, Bioversity International descriptors for tomato have been widely used by germplasm banks and breeders (Mazzucato et al., 2008; Gonçalves et al., 2009; de Castro et al., 2010; Cebolla-Cornejo et al., 2013; Cortés-Olmos et al., 2015; Figàs et al., 2015; Parisi et al., 2016). These reports generally show that IPGRI (1996) descriptors display a large range of variation and are useful to distinguish among accessions and varietal groups. However, amazingly, in most of the cases where germplasm is characterized using IPGRI (1996) descriptors they contain data of a single location and year, and there are few works reporting data of several years or environments. One exception is the work done by Mazzucato et al. (2008), whom used 22 morpho-physiological traits, largely conforming with IPGRI (1996) tomato descriptors, in 61 tomato and wild relatives accessions grown in two locations. In this work, significant genotype × environment interaction was found for 21 out of the 22 descriptors, although the authors indicate that this interaction was mostly caused by the performance of a few genotypes for each trait (Mazzucato et al., 2008). In another work, Rao et al. (2006) used UPOV descriptors to evaluate 'San Marzano' accessions for three years. These authors found that some homogeneous accessions that matched the 'San Marzano' type in one year did not match it in other years. Overall, these data seem to indicate that, while IPGRI (1996) tomato descriptors are appropriate for describing the main morphological characteristics of tomato materials as well as for assessing variation in germplasm and breeding collections, their values and scores may be influenced by the environment and by genotype × environment interaction.

The lack of information on the stability of morphological descriptors in tomato in different environments contrasts with the large number of studies evaluating the

effects of genotype × environment in tomato for agronomic and fruit quality traits (Ortiz et al., 2007; Cebolla-Cornejo et al., 2011; Adalid et al., 2012; Panthee et al., 2012, 2013). In general, these works reveal that there is a large genotype × environment interaction for yield and composition traits, and a moderate or low one for fruit shape traits. Given the importance of standardized descriptors, like those of IPGRI (1996), in tomato germplasm management and in breeding, it is necessary to have an assessment of the genotype × environment interaction of these widely used descriptors, in particular when comparing data from data sets from different environments or years,.

In this work we use a set of IPGRI (1996) descriptors to evaluate 12 tomato accessions in three different cultivation conditions (open-field conventional, open-field organic, and greenhouse conventional). The results will provide information on the stability of the different descriptors in different environmental conditions, and on the utility of the utilization of a multiple set of standardized descriptors for providing a characterization profile that allow differentiation among varieties grown in different environments. All this information will be relevant for tomato germplasm characterization and breeding.

2. Material and methods

2.1. Plant material

Twelve phenotypically diverse local varieties from the region of València (Spain) were used in the present study (Table 1; Figure 1). The accessions belong to seven different cultivar groups of local Valencian varieties (Borseta, Cor, Penjar, Plana, Pruna, Redona, Valenciana) as described in Figàs et al. (2015). Four accessions belong to the Penjar group, which is characterized by the presence of the *alc* mutation, which confers a long shelf-life (Casals et al., 2012), and small or medium-sized fruits, three to the Plana group, characterized by large flattened fruits, and one accession to each of the groups Borseta (pyriform), Cor (slightly heart-shaped), Pruna (cylindrical), Redona (rounded), and Valenciana (heart-shaped) (Table 1).

2.2. Cultivation conditions

All accessions were grown under three cultivation conditions: i) open field under conventional management (open-field conventional), ii) open field under organic management (open-field organic), and iii) greenhouse under conventional management (greenhouse conventional). Seeds for the conventional cultivation trials were disinfected with a 1:10 w/v solution of dodecahydrate trisodium phosphate ($Na_3PO_4 \cdot 12\ H_2O$) for 3 h and rinsed three times with distilled water for 15 min; subsequently, the seeds were subjected to an additional round of disinfection with commercial bleach (40 g/l of NaOCl) at 30% for 7 min and rinsed three times with distilled water for 7 min. After that, the seeds were left to dry for several weeks on filter paper and then subjected to thermotherapy at 80ºC for 24 h. The seeds for the organic cultivation conditions were subjected to the same treatments except that the trisodium phosphate disinfection was not performed. Seedling trays for 96 plants filled with Humin-substrat N3 (Klasmann-Deilmann, Germany) substrate for the conventional cultivation conditions or Natur Pots Premium (Projar) organic substrate for organic conditions were used for sowing the seeds. Seedling trays were kept in a climatic chamber with a 14 h light / 10 h dark photoperiod and a 25ºC (light) / 18 ºC (dark) temperature regime. For the open-field conventional and organic trials, five plants per accession were grown, while for the greenhouse trial six plants per accession were grown. In all trials plants were transplanted on the 23rd of March of 2014, spaced 1.25 m among rows and 0.33 m within the row and distributed according to a completely randomized design.

The open-field conventional trial was located in La Pobla de Vallbona (Valencia, Spain; geographical coordinates: 39º34'33" N, 0º33'13" W, 90 m.a.s.l.). A background fertilization of 0.15 kg/m^2 of fertilizer containing 15% N, 15% P_2O_5, and 15% K_2O (NPK(S) 15-15-15 (20), Fertiberia, Madrid, Spain) was applied before transplant. An additional top-dressing fertilization at a dose of 0.05 kg/m^2 of the same fertilizer was applied three months after transplant. Flood irrigation was used for watering the plants, which were stacked with canes. Weeds were removed manually. Phytosanitary treatments against spider mites, aphids, caterpillars, and tomato leaf miner were performed using spinosad, emamectin, imidacloprid, and dimethoate. A total of six treatments were performed throughout the crop.

The open-field organic trial was also located in La Pobla de Vallbona (Valencia, Spain; 39º34'34" N, 0º33'16" W, 91 m.a.s.l.) in an organic certified farm with a organic cultivation history of 5 years. Fertilization consisted in the background application of 0.6 kg/m^2 of horse manure. Irrigation, plant conduction and weeding were performed as

for the conventional cultivation system. A single phytosanitary treatment using the insecticide spinosad, which is authorized for organic agriculture, was performed.

The greenhouse conventional trial was located in the campus of Universitat Politècnica de València (Valencia, Spain; GPS coordinates: 39º28'56" N, 0º 20' 16'' W, 5 m.a.s.l.). Plants were transplanted to 15 L pots filled with coconut peat (Horticoco, Valimex, Valencia, Spain) and fertilized and watered using a drip irrigation system using pressure compensating emitters. The final concentration of the main anions and cations in the irrigation water was the following: 11.47 mM NO_3^-, 1.00 mM NH_4^+, 1.50 mM $H_2PO_4^-$, 6.75 mM K^+, 3.25 mM Ca^{2+}, 2.50 mM Mg^{2+} and 2.82 mM SO_4^{2-}. Microminerals were supplied by adding the following salts to the irrigation water: 50 μM H_3BO_3, 10 μM FeEDTA, 4.5 μM $MnCl_2$, 3.8 μM $ZnSO_4$, 0.3 μM $CuSO_4$ and 0.1 μM $(NH_4)_6Mo_7O_{24}$. Excess water was applied in order to avoid salt build up in the pots. Plants were trellised using vertical strings. Phytosanitary treatments against spider mites and whiteflies were performed using the following pesticides: spinosad, emamectin, imidacloprid, and dimethoate. A total of six treatments were performed throughout the crop.

2.3. Characterization

Individual plants were characterized using 36 morphological and agronomic descriptors, of which 31 were IPGRI (1996) descriptors (Table 2), which are commonly used in tomato germplasm characterization trials (Mazzucato et al., 2008; Gonçalves et al., 2009; de Castro et al., 2010; Cebolla-Cornejo et al., 2013; Cortés-Olmos et al., 2015; Figàs et al., 2015; Parisi et al., 2016). All characterizations were performed jointly by the same characterization team (MF, SS and CC). The five other descriptors corresponded to yield, fruit firmness, and CIELAB fruit colour parameters L*, h*, and c*, which are traits of relevance for tomato breeding (Rodríguez-Burruezo et al., 2005; Figàs et al., 2005a). Twelve traits were quantitative, four meristic, 17 measured in a quantitative scale, and three dichotomous. IPGRI descriptors data were taken according to the instructions and recommendations given in IPGRI (1996). All fruits of each plant were used to determine yield. Fruit firmness and fruit colour were determined in three fruits (with three measures in three different areas of the mid-part of the fruit separated by 120º) per plant when available using, respectively, a Fruit Pressure Tester FT327 (Effegi, Alfonsine, Italy) with a 8-mm tip probe, and a CR-300 (Minolta, Osaka, Japan)

chromameter. Each plant was considered as a replicate; so multiple measurements from a single plant were used to obtain an average of each plant.

2.4. Data analyses

Individual plant data were used to calculate the mean value for each accession in each of the environments. Average data of accessions in each environment were used to calculate the global mean and range for each of the descriptors. Individual plant data were subjected to a two factorial analysis of variance (ANOVA) to test the effects of accession and cultivation environment, their interaction and the residual effects (Little and Hills, 1978). The total sums of squares was partitioned in the sums of squares for accession, environment, accession × environment, and residual effects, and expressed in percentage over the total sums of squares. Broad sense heritability (H^2) was calculated according to Wricke and Weber (1986) using the formula $H^2 = \sigma_G^2 / [\sigma_G^2 + \sigma_{GE}^2/e + \sigma_E^2/(r \times e)]$, where σ_G^2 is the genetic variance, σ_{GE}^2 is the genotype × environment interaction, σ_E^2 is the residual (error) variance, e is the number of environments (e=3), and r is the average number of replicates per environment (r=[5+5+6]/3) (Wricke and Weber, 1986). Differences among environments for each descriptor were assessed using a Student-Newman-Keuls multiple range test at a significance level of $P<0.05$. Pairwise Euclidean distances among the three cultivation environments were calculated for each accession using standardized data ($\mu=0$; $\sigma=1$) for each descriptor. These pairwise Euclidean distances were also used for a multivariate principal components analysis (PCA).

3. Results

3.1. Descriptors range of variation

None of the 36 descriptors assessed was uniform in the data from 12 accessions evaluated in three environments (Table 2). In general, for quantitative and meristic traits, wide ranges of variation were found. For example, differences of over 11-fold were found for Size of corky area around pedicel scar, of almost 10-fold for Number of locules, and of around seven-fold for Yield per plant, Number of flowers per

inflorescence, and Fruit weight (Table 2). In other traits, the differences were smaller in relative terms, but also reflected a wide variation in the collection of accessions grown in three environments. For traits measured in a quantitative scale, in some cases like Inflorescence type, Intensity of greenback (shoulder), Fruit size homogeneity, Fruit shoulder shape, Fruit cross-sectional shape, Fruit blossom end shape, Radial cracking, and Fruit fasciation, the full scale range as given in the IPGRI (1996) descriptors for tomato was represented (Table 2). However, in other cases, the range variation observed for quantitative scale traits was reduced, like for Leaf attitude (only values of 6 and 7 for a scale from 3 to 7), or for Exterior colour of immature fruit (with values from 1 to 5 for a scale from 1 to 9). For the three dichotomous traits, variation was found in the collection, although most of the accessions presented one of the descriptor states (e.g. "standard" for Leaf type, "present" for Presence of green (shoulder) trips on the fruit, and "yellow" for the skin colour of ripe fruit) (Table 2).

3.2. Structure of descriptors variation

The decomposition of the sums of squares from the ANOVA analyses revealed that the accession effect was highly significant ($P<0.001$) for the 36 descriptors evaluated (Table 3). The percentage of sums of squares for accession varied between 10.83% for Yield per plant and 100.00% for Leaf type and Skin colour for ripe fruit. The accession effect was the largest contributor to the sums of squares for 31 out of the 36 traits evaluated, the exception being for Leaf attitude, Leaf type, Yield per plant, and Number of inflorescences. For 26 traits, the contribution of accession to the sum of squares was higher than 50% (Table 3). The environment effect was low for most traits, with 27 traits out of the 36 evaluated with a contribution below 10% to the total sums of squares. The largest values were observed for Yield per plant (68.34%), which was the only trait for which the environment effect was the largest contributor to the sums of squares, and for Concentric cracking (27.71%) (Table 3). The contribution of the accession × environment interaction to the total sums of squares was generally higher than that of environment. The only traits for which the environment effect had a larger contribution than accession × environment interaction to the total sums of squares were Yield per plant and Number of flowers per inflorescence. The accession × environment interaction effect was the greatest contributor to the total sums of squares for three traits (Leaf attitude, Number of inflorescences, and Flesh colour intensity) (Table 3). The

residual effect contribution to the sums of squares was variable, ranging from 0.00% for Leaf attitude, Leaf type, Presence of green (shoulder) trips on the fruit, Skin colour of ripe fruit, and Puffiness appearance, to 39.47% for Number of leaves under 1st inflorescence. The residual effect was not the greatest contributor to the total sums of squares for any of the descriptors (Table 3).

Heritability (H^2) values ranged between 0.14 for Leaf attitude to 1.00 for Leaf type and Skin colour of ripe fruit (Table 3). For 10 traits out of 36, the H^2 values were higher than 0.7, for 21 descriptors the H^2 values ranged between 0.3 and 0.7, and for five descriptors the H^2 values were below 0.3. The traits with larger H^2 values included Leaf type, some fruit size and shape descriptors (Fruit weight, Fruit length, Fruit width, Size of corky area around pedicel scar, Size of core, Number of locules, and Fruit fasciation), and Skin colour of ripe fruit. The lowest values for H^2 were for Leaf attitude, Yield per plant, Number of inflorescences, Exterior colour of immature fruit, and Puffiness appearance (Table 3).

3.3. Differences among environments

Significant differences ($P<0.05$) among average values in each environment were observed for all descriptors, except for Leaf type, Skin colour of ripe fruit, and Number of locules (Table 4). Plants from the open-field conventional environment were characterized by higher yield and number of flowers per inflorescence, greater fruit size homogeneity, larger values for several descriptors related to fruit size, more intensely coloured fruits, and fruits with higher degree of fasciation and puffiness, as well as less bifurcated inflorescences and less firm fruits than those of the open field-organic or greenhouse environments (Table 4). Those from the open-field organic environment had plants with smaller size, more erect leaves, less number of flowers per inflorescence, with a greater proportion and intensity of green shoulder, less fruit size homogeneity, thinner pericarp, less fruit colour intensity, more pointed fruits, and with higher cracking incidence than those of open-field organic or greenhouse cultivation. Finally, plants from the greenhouse environment had a higher vegetative development with dropping leaves, immature fruits less green, and with less intensity of greenback in the shoulder, smaller fruits, with less cracking and fasciation, and with lower fruit colour lightness than those of open-field cultivation (Table 4).

When considering all descriptors together, the three environments were almost equidistant, with pairwise Euclidean differences averaged over the 12 varieties among them not being significantly different for the three possible comparisons (Table 5). However, the accessions evaluated had a different performance, with highest values for accession MA2 (Pruna type) with an average value of 8.01 for Euclidean distances among environments, while for one accession of the Cor type (DA2) and two Penjar accessions (VI1 and VS1) the average Euclidean distances among environments were much smaller, below 5. When considering specific pairwise comparisons in individual accessions, the range of Euclidean distances among environments varies between 3.56 for VS1 for the open-field conventional vs. greenhououse environments comparison, and 8.81 for MA2 for the open-field conventional and open field-organic environments comparison. Also, for five accessions (AX2, DA2, MA2, RE2, and XA1) the largest environmental distances were found between open-field conventional and open-field organic environments, for two accessions (PI1 and VS1) were between open-field conventional and greenhouse environments, while for six accessions were between open-field organic and greenhouse environments (Table 5).

3.4. Principal components analysis

The first and second components of the PCA made with 36 descriptors evaluated accounted for 30.21% and 14.06%, respectively, of the total variance (Table 6). The first principal component was positively correlated to descriptors related to divided inflorescences (Inflorescence type), multiple fruit size and weight descriptors, large pedicel scars and corky area around them, intensely coloured fruits, irregular cross section (Fruit cross-sectional shape, Fasciation and Number of locules), Size of core and Radial cracking, and negatively to Fruit size homogeneity, Thickness of pericarp and Fruit firmness (Table 6). The second principal component was positively correlated to Foliage density, dropping (Leaf attitude) and standard (Leaf type) leaves, number of inflorescences, Fruit size and Fruit length, yellow colour of ripe fruit (Skin colour of ripe fruit), and Exterior fruit chroma value (c*), and negatively with indeterminate growth (Plant growth type), Number of leaves under 1st inflorescence, Number of flowers per inflorescence, Presence of green (shoulder) trips on the fruit, and Exterior fruit colour lightness (L*) and hue (h*).

The projection of accessions grown in each of the environments in the PCA plot reveals that the different cultivar groups plot in separated areas of the graph, with the exception of Cor and Redona groups, which cluster together (Figure 2). The first component separates accessions of the Plana (large and fascinated fruits) and Valenciana type (large fruits), which generally present positive values for this first component from those of the Pruna, Penjar and Borseta types, which have negative values. The second component separates the Pruna, Cor, Redona, Valenciana and Borseta types, which have positive values from the Penjar type, which displays negative values (Figure 2). Accessions grown in the three different environments group together, and generally are separated from the other accessions, with the exception of accessions DA2 (Cor type) and XA1 (Redona type) on one side, and accessions AX1, VI1, and VS1 (Penjar type) on the other, which are intermingled (Figure 2). Accessions of the Plana type are separated in the first component, with FU1, RE2 and OR3 having highest, intermediate and lower values, respectively. The AX2 (Penjar) accession is characterized by having a combination of lower values for the first component and higher ones for the second component than the rest of Penjar accessions (Figure 2).

4. Discussion

Our work is the first, to our knowledge, to evaluate the stability of tomato descriptors in characterization trials from different cultivation environments. Amazingly, despite the importance of characterization data for breeding and germplasm management (Engels and Visser, 2002; Ortiz Ríos, 2015), there is little information on the stability of tomato descriptors and the influence this may have in comparison of data sets from different trials and environments.

We have found that the morphological and agronomic descriptors used, most of them corresponding to the Bioversity International descriptors list for tomato (IPGRI, 1996), are useful to describe the variation existing in a collection of tomato local varieties, with wide ranges of variation having being observed, as occurred in other works (Mazzucato et al., 2008; Gonçalves et al., 2009; de Castro et al., 2010; Cebolla-Cornejo et al., 2013; Cortés-Olmos et al., 2015; Figàs et al., 2015; Parisi et al., 2016). This again confirms the utility of these descriptors for providing a description for relevant traits in tomato, as well as for comparing varieties and cultivar groups from a single trial. In our case, we have compared data from three different cultivation

environments in three different sites. In order to evaluate the descriptors in different environments, we included open-field conventional, open-field organic and greenhouse cultivation conditions.

Ideally, descriptors should have high heritability and, in consequence, the cultivation environment and genotype × environment interaction should have a low influence in the expression of the trait scored (Ortiz Ríos, 2015). This would allow direct comparisons among characterization data sets. However, the comparison of the scores of the same descriptors in three characterization trials revealed that wide differences exist among descriptors for the effects of environment and genotype × environment. This is in agreement with some previous evidence (Rao et al., 2006; Mazzucato et al., 2008). These latter authors reported significant genotype × environment interaction for morphological descriptors in the characterization of specific sets of local tomato varieties in different environments. However, these studies do not provide information on the relative contribution of the environment or genotype × environment interaction to the variation of descriptors (Rao et al., 2006; Mazzucato et al., 2008). In our work, we have found large differences among individual descriptors in the contribution of the accession, environment, or genotype × environment interaction effects. In this respect, descriptors for some monogenic traits, like Leaf type, controlled by gene *C* (Busch et al., 2011), or Skin colour, controlled by gene *Y* (Ballester et al., 2010), are not influenced by the environment and display no genotype × environment interaction and therefore have a heritability of 1. Other traits that had relatively high values for heritability were those related to fruit shape. In tomato, it is known that the expression of fruit shape traits has a high degree of genetic determination (Gonzalo and van der Knaap, 2008, Rodríguez et al., 2011). On the other side, other descriptors, for important traits, like yield per plant, had high environmental influence and genotype × environment interaction, as well as differences among plants within a trial, and therefore have a low heritability. This is in agreement with other works (Avdikos et al., 2011; El-Gabry et al., 2014), that reveal that yield, being a complex trait affected by multiple genetic factors affected by the environment generally has a low heritability. Remarkably, few descriptors had high heritability values, with only 10 out of the 36 descriptors having a heritability value above 0.7. This is in contrast with the recommendation that descriptors for germplasm characterization should have high heritability (Ortiz Ríos, 2015). It also suggests that comparisons of data sets corresponding to different trials, in particular, when environmental conditions are very

405 dissimilar should be made with caution, unless only descriptors with high heritability or
406 low genotype × environment contribution to the observed variation are used. In this
407 respect, the fact that for most descriptors the contribution of the genotype ×
408 environment effect is larger than that of the environment indicates that the use of
409 controls or environmental indexes to remove the environmental effect may only
410 partially contribute to make data comparable (Wricke and Weber, 1986; Becker and
411 Léon, 1988).

412 The three cultivation systems that we have evaluated presented many differences
413 in the crop management (Martínez-Blanco et al., 2011; van Bueren et al., 2011; de Ponti
414 et al., 2012). This has resulted in many significant differences among environments for
415 the traits evaluated. In particular, average yield has been much higher in the open-field
416 conventional environment than in the open-field organic or greenhouse environments,
417 probably reflecting the reduced input of fertilizers in the organic field and the poor
418 performance of many local tomato varieties in greenhouse (Bettiol et al., 2004; Jones,
419 2007; Kläring and Krumbein, 2013). The higher incidence of fruit cracking in the open-
420 field organic than in the open-field conventional conditions suggests that there has been
421 higher fluctuation of soil water content in the soil and/or deficiencies of calcium or
422 boron that, apart from increasing cracking may have contributed to reduce yield
423 (Pascual et al., 2000; Liebisch et al., 2009). The differences among environments for
424 each accession have also been studied using pairwise Euclidean distances among the
425 standardized values for the 36 descriptors. While the three environments were
426 approximately equidistant when considering the average values across all varieties,
427 considerable differences have been observed among varieties, both in the average value
428 and the environmental distances among pairs of environments. In this respect, some
429 varieties were more stable than others, and consequently had lower differences for
430 characterization data among environments. Others, on the contrary displayed much
431 higher differences among environments, reflecting a lower stability. Important
432 differences in stability for several traits have been observed in tomato (Ortiz and
433 Izquierdo, 1994). This has implications when choosing controls for comparison of
434 environments, as depending on the variety or varieties chosen, the estimation of the
435 environmental effect may be variable (Annicchiarico, 2002).

436 Despite wide differences among individual descriptors for the contribution of the
437 environment and genotype × environment effects to their variation, the multivariate
438 principal component analysis (PCA) shows that observations of a single accession

grown in different environments plot in the same area of the PCA graph. This indicates that IPGRI (1996) descriptors, despite the fact that some of them have low heritability, when analyzed together provide a reliable characterization. As found in other works (Cebolla-Cornejo et al., 2013; Figàs et al., 2015), the IPGRI (1996) morphological descriptors allow a clear separation among tomato cultivar groups. However, the PCA analysis also reveals that for accessions of the same cultivar group, some of the accessions are intermingled, and therefore the comparison of characterization data of different accessions of the same cultivar group evaluated in different environments could lead to misleading results about the relationships among them. This has important implications for detecting duplicates and creating nuclear collections in germplasm banks (Dwivedi et al., 2005; Diederichsen, 2009), as a genetically uniform accession evaluated in one environment when compared to itself and other accessions of the same cultivar group grown in another environment may plot closer to other accessions. Similarly, different accessions evaluated in different environment can plot together in a PCA analysis.

5. Conclusions

In conclusion, our work confirms that morphological and agronomic descriptors commonly used for characterization of tomato, like those of IPGRI (1996), are suited for providing a detailed description of germplasm accessions or other plant materials. This makes them of great utility for evaluating diversity, to study relationships among accessions, and to assign them to cultivar groups. However, many descriptors, when compared over dissimilar environments, have low or moderate heritability. This, coupled with large genotype × environment interaction effects indicates that comparison of tomato characterization data sets that include accessions that have not been grown in the same trial should be made with caution, even when controls are used to remove the environmental effect. Nonetheless, multivariate principal components analysis using data coming from different environments have proved useful for a reliable separation of accessions according to cultivar group. All this information has important implications for tomato germplasm conservation and management as well as for breeding.

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References

Adalid, A.M., Roselló, S., Valcárcel, M., Nuez, F., 2012. Analysis of the genetic control of β-carotene and L-ascorbic acid accumulation in an orange-brownish wild cherry tomato accession. Euphytica 184:251-263.

Annicchiarico, 2002. Genotype × environment interactions – challenges and opportunities for plant breeding and cultivar recommendations. Food and Agriculture Organization of the United Nations, Rome.

Avdikos, I.D., Tsivelika, N., Gallidou, A., Koutsika-Sotirou, M., 2011. Exploitation of heterosis in tomato recurrent selection programme applied in segregating generations of a tomato breeding program. Sci. Hort. 130:701-707.

Ballester, A.R., Molthoff, J., de Vos, R., Hekkert, B.L., Orzaez, D., Fernández-Moreno, J.P., Tripodi, P., Grandillo, S., Martin, C., Heldens, J., Ykema, M. Granell, A., Bovy, A., 2010. Biochemical and molecular analysis of pink tomatoes: deregulated expression of the gene encoding transcription factor S1MYB12 leads to pink tomato fruit color. Plant Physiol. 152:71-84.

Becker, H.C., Léon, J., 1988. Stability analysis in plant breeding. Plant Breed. 101:1-23.

Bettiol, W., Ghini, R., Galvão, J.A.H., Siloto, R.C., 2004. Organic and conventional tomato cropping systems. Sci. Agric. 61:253-259.

Bioversity International, 2017. Crop descriptors and derived standards. https://www.bioversityinternational.org/e-library/publications/descriptors/

Busch, B.L., Schmitz, G., Rossmann, S., Piron, F., Ding, J., Bendahmane, A., Theres, K., 2011. Shoot branching and leaf dissection in tomato are regulated by homologous gene modules. Plant Cell 23:3595-3609.

Casals, J., Pascual, L., Cañizares, J., Cebolla-Cornejo, J., Casañas, F., Nuez, F., 2012. Genetic basis of long shelf life and variability into Penjar tomato. Genet. Resour. Crop Evol. 59:219-229.

Cebolla-Cornejo, J., Roselló, S., Valcárcel, M., Serrano, E., Beltrán, J., Nuez, F., 2011. Evaluation of genotype and environment effects on taste and aroma components of Spanish fresh tomato varieties. J. Agric. Food Chem. 59:2440-2450.

Cebolla-Cornejo, J., Roselló, S., Nuez, F., 2013. Phenotypic and genetic diversity of Spanish tomato landraces. Sci. Hort. 162:150-164.

Cortés-Olmos, J., Vilanova, S., Pascual, L., Roselló, S., Cebolla-Cornejo, J., 2015. SNP markers applied to the characterization of Spanish tomato (*Solanum lycopersicum* L.) landraces. Sci. Hort. 194:100-110.

de Castro, J.P.A., Nick, C., Milagres, C.C., Mattedi, A.P., Marim, B.G., da Silva, D.J.H., 2010. Genetic diversity among tomato's subsamples for pre-breeding. Crop Breed. Appl. Biotech. 10:74-82.

de Ponti, T., Rijk, B., van Ittersum, M.K., 2012. The crop yield gap between organic and conventional agriculture. Agr. Syst. 108:1-9.

Diederichsen, A., 2009. Duplication assessments in Nordic *Avena sativa* accessions at the Canadian national genebank. Genet. Resour. Crop Evol. 56:587-597.

Dwivedi, S., Upadhyaya, H.D., Hedge, D.M., 2005. Development of core collection using geographic information and morphological descriptors in safflower (*Carthamus tinctorius* L.) germplasm. Genet. Resour. Crop Evol. 52:821-830.

El-Gabry, M.A.H., Solieman, T.I.H., Abido, A.I.A., 2014. Combining ability and heritability of some tomato (*Solanum lycopersicum* L.) cultivars. Sci. Hort. 167:153-157.

Engels, J., Visser, B., 2002. Genebank management procedures. In: Engels, J.M.M., Visser, L. (eds) A guide to effective management of germplasm collections. IPGRI Handbooks for genebanks No. 6. International Plant Genetic Resources Institute, Rome, pp. 60-79.

Figàs, M.R., Prohens, J., Raigón, M.D., Fernández-de-Córdova, P., Fita, A., Soler, S., 2015. Characterization of a collection of local varieties of tomato (*Solanum lycopersicum* L.) using conventional descriptors and the high-throughput phenomics tool Tomato Analyzer. Genet. Resour. Crop Evol. 62:189-204.

Gonçalves, L.S.A., Rodrigues, R., Júnior, A.T.A., Karasawa, M., Sudré, C.P., 2009. Heirloom tomato gene bank: assessing genetic divergence based on

538 morphological, agronomic and molecular data using a Ward-modified location
539 model. Genet. Mol. Res. 8:364-374.
540 Gonzalo, M.J., van der Knaap, E., 2008. A comparative analysis into the genetic bases
541 of morphology in tomato varieties exhibiting long shape. Theor. Appl. Genet.
542 116:647-656.
543 Gotor, E., Alercia, A., Rao, V.R., Watts, J., Caracciolo, F., 2008. The scientific
544 information activity of Bioversity International: the descriptors lists. Genet.
545 Resour. Crop Evol. 55:757-772.
546 Grum, M., Atieno, F., 2007. Statistical analysis for plant genetic resources: clustering
547 and indices in R made simple. IPGRI Handbooks for genebanks No. 9.
548 International Plant Genetic Resources Institute, Rome.
549 IPGRI, 1996. Descriptors for tomato (*Lycopersicon* spp.). International Plant Genetic
550 Resources Institute, Rome.
551 Jones, J.B., 2007. Tomato plant culture – in the field, greenhouse and home garden.
552 CRC Press, Boca Raton, FL, USA.
553 Kläring, H.P., Krumbein, A., 2013. The effect of constraining the intensity of solar
554 radiation on the photosynthesis, growth, yield and product quality of tomato. J.
555 Agron. Crop Sci. 199:351-359.
556 Liebisch, F., Max, J.F.J., Heine, G., Horst, W.J., 2009. Blossom-end rot and fruit
557 cracking of tomato grown in net-covered greenhouses in Central Thailand can
558 partly be corrected by calcium and boron sprays. J. Plant Nutr. Soil Sci.
559 172:140-150.
560 Little, T.M., Hills, F.J., 1978. Agricultural experimentation: design and analysis. Wiley,
561 New York, NY.
562 Martínez-Blanco, J., Muñoz, P., Antón, A., Rieradevall, J., 2011. Assessment of tomato
563 Mediterranean production in open-field and standard multi-tunnel greenhouse,
564 with compost or mineral fertilizers, from an agricultural and environmental
565 standpoint. J. Cleaner Prod. 19:985-987.
566 Mazzucato, A., Papa, R., Bitocchi, E., Mosconi, P., Nanni, L., Negri, V., Picarella M.E.,
567 Siligato, F., Soressi, G.P., Tiranti, B., Veronesi, F., 2008. Genetic diversity,
568 structure and marker-trait associations in a collection of Italian tomato (*Solanum*
569 *lycopersicum* L.) landraces. Theor. Appl. Genet. 116:657-669.
570 Panthee, D.R., Cao, C., Debenport, S.J., Rodríguez, G.R., Labate, J.A., Robertson, L.D.,
571 Breksa, A.P., van der Knaap, E., Gardener B.B.M., 2012. Magnitude of

572 genotype × environment interactions affecting tomato fruit quality. HortScience
573 47:721-726.
574 Panthee, D.R., Labate, J.A., McGrath, M.T., Breksa A.P., Robertson, L.D., 2013.
575 Genotype and environmental interaction for fruit quality traits in vintage tomato
576 varieties. Euphytica 193:169-182.
577 Pascual, B., Maroto, J.V., Sanbautista, A., López-Galarza, S., Alagarda, J., 2000.
578 Influence of watering on the yield and cracking of cherry, fresh-market and
579 processing tomatoes. J. Hort. Sci. Biotechnol. 75:171-175.
580 Ortiz, R., Crossa, J., Vargas, M., Izquierdo, J., 2007. Studying the effect of
581 environmental variables on the genotype × environment interaction of tomato.
582 Euphytica 153:119-134.
583 Ortiz, R., Izquierdo, J., 1994. Yield stability differences among tomato genotypes
584 grown in Latin America and the Caribbean. HortScience 29:1175-1177.
585 Ortiz Ríos, R., 2015. Plant genetic resources for food and agriculture. In: Ortiz Ríos, R.
586 (ed) Plant breeding in the omics era. Springer, New York, pp. 19-39.
587 Parisi, M., Aversano, R., Graziani, G., Ruggieri, V., Senape, V., Sigillo, L., Barone, A.,
588 2016. Phenotypic and molecular diversity in a collection of 'Pomodoro di
589 Sorrento' Italian tomato landrace. Sci. Hort. 203:143-151.
590 Rao, R., Corrado, G., Bianchi, M., Di Mauro, A., 2006. $(GATA)_4$ DNA fingerprinting
591 identifies morphologically characterized 'San Marzano' tomato plants. Plant
592 Breed. 125:173-176.
593 Robertson, L.D., Labate, J.A., 2006. Genetic resources of tomato (*Lycopersicon*
594 *esculentum* Mill.) and wild relatives. In: Razdan, M.K., Mattoo, A.K. (eds)
595 Genetic improvement of solanaceous crops. Volume 2: Tomato. CRC Press,
596 Boca Raton, FL, USA, pp. 25-75.
597 Rodríguez, G.R., Muñoz, S., Anderson, C., Sim, S.C., Michel, A., Causse, M.,
598 McSpadden Gardener, B.B., Francis, D., van der Knaap, E., 2011. Distibution of
599 *SUN, OVATE, LC* and *FAS* in the tomato germplasm and the relationship to fruit
600 shape diversity. Plant Physiol. 156:275-285.
601 Rodríguez-Burruezo, A., Prohens, J., Roselló, S., Nuez, F., 2005. "Heirloom" varieties
602 as sources of variation for the improvement of fruit quality in greenhouse-grown
603 tomatoes. J. Hort. Sci. Biotech. 80:453-460.
604 UPOV, 2017. Test guidelines. http://www.upov.int/en/publications/tg-rom/tg_index.htm

van Bueren, E.T.L., Jones, S.S., Tamm, L., Murphy, K.V., Myers, J.R., Leifert, C., Messmer, M.M., 2011. The need to breed crop varieties suitable for organic farming, using wheat, tomato and broccoli as examples: A review. NJAS-Wageningen J. Life Sci. 58:193-205.

van Ittersum, M.K., Cassman, K.G., Grassini, P., Wolf, J., Tittonell, P., Hochman, Z., 2013. Yield gap analysis with local to global relevance – A review. Field Crops Res. 143:4-17.

Wricke, G., Weber, W.E., 1986. Quantitative genetics and selection in plant breeding. Walter de Gruyter, Berlin.

Table 1

Local tomato varieties used for the present study including the varietal type (according to Figàs et al., 2015), and origin (municipality and province) within the Valencian Region (Spain).

Accession code	Varietal type	Predominant fruit shape	Origin	
			Municipality	Province
AX1	Penjar	Flattened	Alcalà de Xivert	Castelló
AX2	Penjar	Rounded	Alcalà de Xivert	Castelló
DA2	Cor	Slightly heart-shaped	Dos Aigües	València
FU1	Plana	Flattened	Fuenterrobles	València
MA2	Pruna	Cylindrical	Massalfassar	València
OR1	Borseta	Pyriform	Oriola	Alacant
OR3	Plana	Flattened	Oriola	Alacant
PI1	Valenciana	Heart-shaped	Picanya	València
RE2	Plana	Flattened	Requena	València
VI1	Penjar	Slightly flattened	Vinaròs	Castelló
VS1	Penjar	Flattened	Vistabella	Castelló
XA1	Redona	Rounded	Xàtiva	València

620

621 **Table 2**

622 Descriptors used and the global mean and range of varietal means observed in the three environments evaluated in the 12 local tomato varieties

623 studied. Full details of the Bioversity International descriptors can be consulted elsewhere (IPGRI, 1996).

Descriptors	IPGRI descriptor code	Units/scale	Mean	Range
		Plant descriptors		
Plant growth type	7.1.2.1	1=Dwarf; 4=Indeterminate	3.73	2.00-4.00
Foliage density	7.1.2.6	3=Sparse; 7=Dense	5.23	4.00-7.00
Number of leaves under 1st inflorescence	7.1.2.7	---	7.84	5.00-12.50
Leaf attitude	7.1.2.8	3=Semi-erect; 7=Dropping	6.86	6.00-7.00
Leaf type[a]	7.1.2.9	2=Potato leaf; 3=Standard	2.92	2.00-3.00
Yield per plant	---	g	2776	883-6167
		Inflorescence descriptors		
Inflorescence type	7.2.1.1.	1=Generally uniparous; 3=Generally multiparous	2.03	1.00-3.00
Number of inflorescences	8.1.4	---	7.70	3.50-24.60
Number of flowers per inflorescence	8.1.5	---	7.22	4.48-11.44
		Fruit descriptors		
Exterior colour of immature fruit	7.2.2.1	1=Greenish-white; 9=Very dark green	2.29	1.00-5.00

Presence of green (shoulder) trips on the fruit	7.2.2.2	0=Absent; 1=Present	0.94	0.00-1.00
Intensity of greenback (shoulder)	7.2.2.3	3=Slight; 7=Strong	4.51	0.00-7.00
Fruit size	7.2.2.6	1=Very small; 5=Very large	3.43	2.00-5.00
Fruit size homogeneity	7.2.2.7	3=Low; 7=High	5.21	2.00-7.00
Fruit weight	7.2.2.8	g	165.8	62.2-446.9
Fruit length	7.2.2.9	mm	60.8	40.7-94.6
Fruit width	7.2.2.10	mm	72.0	46.0-116.4
Fruit shoulder shape	7.2.2.16	1=Flat; 7=Strongly depressed	3.39	1.00-7.00
Width of pedicel scar	7.2.2.20	mm	10.7	5.7-19.6
Size of corky area around pedicel scar	7.2.2.21	mm	3.60	0.88-10.10
Skin colour of ripe fruit	7.2.2.23	1=Colourless; 2=Yellow	1.75	1.00-2.00
Thickness of pericarp	7.2.2.25	mm	7.42	5.10-9.90
Flesh colour intensity	7.2.2.27	3=Light; 7=Dark	5.78	4.00-7.00
Colour (intensity) of core	7.2.2.28	1=Green; 7=Dark	4.74	2.00-7.00
Fruit cross-sectional shape	7.2.2.29	1=Round; 3=Irregular	1.62	1.00-3.00
Size of core	7.2.2.30	cm	3.62	1.43-7.31
Number of locules	7.2.2.31	---	6.54	2.00-19.60
Fruit blossom end shape	7.2.2.33	1=Indented; 3=Pointed	1.63	1.00-3.00
Radial cracking	8.2.3	1=Corky lines; 7=Severe	2.83	0.00-7.00
Concentric cracking	8.2.4	1=Corky lines; 7=Severe	1.24	0.00-5.00

Fruit fasciation	8.2.5	3=Slight; 7=Severe	2.31	0.00-7.00
Puffiness appearance	8.2.9	3=Slight; 7=Severe	1.19	0.00-6.00
Fruit firmness	---	kg/cm^2	1.90	1.29-2.84
Exterior fruit colour lightness (L*)	---	0=black; 100=white	36.3	29.5-46.9
Exterior fruit colour hue (h*)	---	0^o=red; 90^o=yellow; 180^o=green; 270^o=blue	36.7	25.7-56.0
Exterior fruit colour chroma (c*)	---	0=completely unsaturated; 100=fully saturated	26.0	16.1-35.4

624 [a] Qualitative descriptor potentially polytomous, but which has been found to be dichotomous in the collection

Table 3

Percentage of the total sums of squares for the effects of accessions, environment, interaction between accession and environment and residuals for the descriptors evaluated in 12 tomato accessions grown in three environments.

Descriptors	Sums of squares (%)[a]				Heritability (H^2)
	Accession	Environment	Accession × Environment	Residual	
Plant growth type	64.19***	1.97***	12.94***	15.15	0.57
Foliage density	59.69***	17.79***	19.98***	2.53	0.61
Number of leaves under 1st inflorescence	48.43***	5.22***	6.87ns	39.47	0.49
Leaf attitude	35.33***	17.60***	47.07***	0.00	0.14
Leaf type	100.00***	0.00ns	0.00ns	0.00	1.00
Yield per plant	10.83***	68.34***	6.45***	14.38	0.25
Inflorescence type	67.78***	2.44***	10.62***	19.17	0.65
Number of inflorescences	36.50***	4.61***	40.79***	18.09	0.17
Number of flowers per inflorescence	50.16***	14.63***	7.92**	27.29	0.56
Exterior colour of immature fruit	49.96***	0.41***	48.74***	0.88	0.26
Presence of green (shoulder) trips on the fruit	65.31***	2.89***	31.80***	0.00	0.51
Intensity of greenback (shoulder)	56.89***	17.98***	24.86***	0.27	0.54
Fruit size	76.90***	3.25***	18.64***	1.21	0.70
Fruit size homogeneity	66.27***	5.72***	27.58***	0.44	0.56

Fruit weight	71.37***	10.80***	12.38***	5.45	0.73
Fruit length	80.89***	4.42***	7.37***	7.32	0.81
Fruit width	83.56***	1.64***	5.66***	9.14	0.83
Fruit shoulder shape	85.03***	2.08***	12.38***	0.51	0.81
Width of pedicel scar	54.25***	5.68***	9.04**	31.02	0.54
Size of corky area around pedicel scar	76.83***	1.47***	9.53***	12.18	0.74
Skin colour of ripe fruit	100.00***	0.00ns	0.00ns	0.00	1.00
Thickness of pericarp	52.97***	6.36***	14.80***	25.88	0.50
Flesh colour intensity	31.42***	5.26***	63.32***	0.00	0.00
Colour (intensity) of core	66.36***	1.40***	31.71***	0.53	0.51
Fruit cross-sectional shape	78.55***	0.24***	19.82***	1.38	0.69
Size of core	82.47***	1.02***	9.17***	7.33	0.79
Number of locules	92.68***	0.08ns	1.74***	5.50	0.92
Fruit blossom end shape	74.59***	1.33***	15.18***	8.91	0.68
Radial cracking	51.27***	10.99***	37.38***	0.36	0.37
Concentric cracking	38.41***	27.71***	33.51***	0.36	0.30
Fruit fasciation	88.49***	1.31***	10.13***	0.07	0.85
Puffiness appearance	50.22***	0.04***	49.73***	0.00	0.24
Fruit firmness	46.69***	2.75**	19.33***	31.23	0.39
Exterior fruit colour lightness (L*)	44.35***	10.21***	23.26***	22.17	0.37

Exterior fruit colour hue (h*)	65.69***	7.21***	10.69***	16.42	0.66
Exterior fruit colour chroma (c*)	59.12***	3.68***	12.93***	24.27	0.56

628 [a] ns, *, ***, and *** indicate non-significant, or significant at P<0.05, >0.01, and <0.001, respectively.

Table 4

Values averaged over 12 tomato accessions for each descriptor in the three environments evaluated and significance of differences.

Descriptors	Open field conventional	Open field organic	Greenhouse
Plant growth type[a]	3.75 b	3.61 a	3.82 b
Foliage density	5.33 b	4.83 a	5.53 c
Number of leaves under 1st inflorescence	7.25 a	7.73 a	8.53 b
Leaf attitude	6.92 b	6.67 a	7.00 c
Leaf type[a]	2.92 a	2.92 a	2.92 a
Yield per plant	4717 b	1890 a	1721 a
Inflorescence type	1.87 a	2.15 b	2.08 b
Number of inflorescences	8.73 b	7.42 a	6.96 a
Number of flowers per inflorescence	7.67 b	6.04 a	7.95 b
Exterior colour of immature fruit	2.33 b	2.33 b	2.21 a
Presence of green (shoulder) trips on the fruit	0.92 a	1.00 b	0.92 a
Intensity of greenback (shoulder)	4.25 b	5.50 c	3.79 a
Fruit size	3.50 b	3.53 c	3.25 a
Fruit size homogeneity	5.58 c	4.87 a	5.17 b
Fruit weight	188.9 b	187.0 b	121.5 a
Fruit length	6.48 c	5.96 b	5.81 a
Fruit width	7.53 b	7.08 a	6.98 a
Fruit shoulder shape	3.75 c	3.17 a	3.25 b
Width of pedicel scar	1.16 b	1.08 b	0.95 a
Size of corky area around pedicel scar	0.40 c	0.32 a	0.36 b
Skin colour of ripe fruit	1.75 a	1.75 a	1.75 a
Thickness of pericarp	0.77 b	0.69 a	0.76 b

Flesh colour intensity	5.50 a	5.92 b	5.92 b
Colour (intensity) of core	5.00 c	4.47 a	4.75 b
Fruit cross-sectional shape	1.58 a	1.67 c	1.62 b
Size of core	3.79 c	3.64 b	3.45 a
Number of locules	6.56 a	6.69 a	6.36 a
Fruit blossom end shape	1.58 a	1.75 b	1.56 a
Radial cracking	2.75 b	3.80 c	1.94 a
Concentric cracking	1.43 b	2.20 c	0.08 a
Fruit fasciation	2.58 c	2.42 b	1.93 a
Puffiness appearance	1.25 b	1.17 a	1.17 a
Fruit firmness	1.80 a	1.93 b	1.96 b
Exterior fruit colour lightness (L*)	37.64 c	36.21 b	34.92 a
Exterior fruit colour hue (h*)	40.08 b	34.74 a	35.35 a
Exterior fruit colour chroma (c*)	27.40 b	25.39 a	25.22 a

632 [a]Means within rows separated by different letters are significantly different at P<0.05,
633 according to the Student-Newman-Keuls test.
634

635 **Table 5**

636 Pairwise Euclidean distances among three cultivation environments (open field
637 conventional, open field organic, and greenhouse) for 12 tomato accessions based on
638 normalized data of 36 characterization descriptors.

Accesions	Open field conventional vs. Open field organic	Open field conventional vs. Greenhouse	Open field organic vs. Greenhouse	Average
AX1	4.61	4.90	6.04	5.18
AX2	6.70	4.62	5.33	5.55
DA2	5.06	4.52	4.00	4.53
FU1	4.98	6.10	6.47	5.85
MA2	8.81	7.57	7.65	8.01
OR1	4.96	6.19	6.37	5.84
OR2	5.80	5.80	6.14	5.91
PI1	5.30	5.67	4.87	5.28
RE2	6.05	5.30	4.60	5.32
VI1	4.82	4.77	5.29	4.96
VS1	5.52	3.56	5.67	4.92
XA1	7.09	5.53	4.96	5.86
Average±SE	5.81±0.34	5.38±0.28	5.62±0.27	5.60±0.24

639

640

641 **Table 6**

642 Correlation coefficients between tomato descriptors for plant, inflorescence and fruit of
643 12 accessions grown in three environments and the two first principal components of a
644 multivariate principal components analysis. Correlations with absolute values above
645 0.150 are represented in bold font.

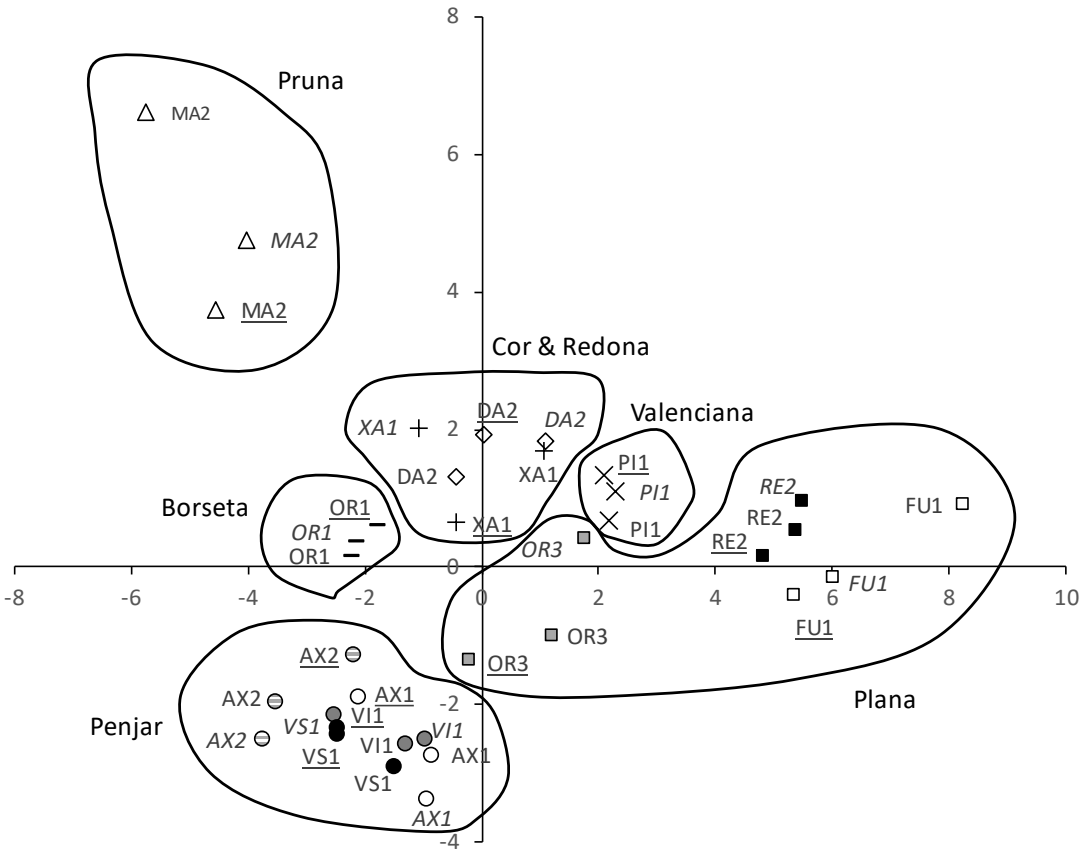
Descriptor	First principal component	Second principal component
Plant growth type	0.089	**-0.335**
Foliage density	-0.039	**0.193**
Number of leaves under 1st inflorescence	-0.023	**-0.271**
Leaf attitude	0.116	**-0.157**
Leaf type[a]	0.060	**0.155**
Yield per plant	0.083	0.054
Inflorescence type	**0.218**	-0.082
Number of inflorescences	-0.122	**0.213**
Number of flowers per inflorescence	0.014	**-0.217**
Exterior colour of immature fruit	-0.076	-0.056
Presence of green (shoulder) trips on the fruit	0.116	**-0.251**
Intensity of greenback (shoulder)	0.104	-0.147
Fruit size	**0.224**	**0.183**
Fruit size homogeneity	**-0.178**	-0.081
Fruit weight	**0.270**	0.094
Fruit length	0.018	**0.372**
Fruit width	**0.292**	0.008
Fruit shoulder shape	**0.272**	-0.019
Width of pedicel scar	**0.264**	0.001
Size of corky area around pedicel scar	**0.267**	0.075
Skin colour of ripe fruit	-0.050	**0.188**
Thickness of pericarp	**-0.171**	-0.040
Flesh colour intensity	0.091	0.145
Colour (intensity) of core	**0.181**	0.141
Fruit cross-sectional shape	**0.191**	-0.121
Size of core	**0.275**	-0.014

Number of locules	**0.288**	0.077
Fruit blossom end shape	-0.070	0.146
Radial cracking	**0.164**	-0.044
Concentric cracking	-0.010	-0.104
Fruit fasciation	**0.212**	-0.103
Puffiness appearance	-0.078	-0.018
Fruit firmness	**-0.203**	0.059
Exterior fruit colour lightness (L*)	-0.104	**-0.168**
Exterior fruit colour hue (h*)	-0.115	**-0.265**
Exterior fruit colour chroma (c*)	-0.040	**0.317**
Eigenvalue	10.88	5.06
Variance explained (%)	30.21	14.06

646

Figure 1

Fruits of the 12 local tomato varieties (AX1 to XA1) from the Valencian Region (Spain) used in the morphological and agronomic characterizations. The varietal type of each of them can be consulted in Table 1. Fruits are not depicted at the same scale; the divisions in the ruler correspond to 1 cm.



654

655 **Figure 2**

656 First (x-axis) and second (y axis) principal components scatterplot, based on 36
657 morphological and agronomic descriptors, of 12 tomato accessions grown under three
658 environments. The first and second principal components account for 30.21% and
659 14.06% of the total variation. Each variety is indicated by its code (AX1 to XA1) and
660 by the varietal type: Borseta (horizontal lines), Cor (diamonds), Penjar (circles), Plana
661 (squares), Pruna (triangles), Redona (plus signs), and Valenciana (multiplication signs).
662 The three cultivation conditions are indicated by the font type: open-field conventional
663 (normal font), open-field organic (italics font), or greenhouse (underlined) cultivation
664 conditions. Lines encompass the accessions included in each cultivar group.

665