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Phenological growth stages of tree tomato (*Solanum betaceum* Cav.), an emerging fruit crop, according to the basic and extended BBCH scales

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ABSTRACT

The tree tomato (*Solanum betaceum* Cav.) is a small tree native to the Andean region cultivated for its juicy fruits, which are having an increasing demand. Tree tomato is morphologically and phenologically different from other *Solanum* crops and tools for the phenological description of the developmental stages are needed for the enhancement of this emerging crop. We developed a basic and an extended numerical BBCH (Biologische Bundesanstalt, Bundessortenamnt, Chemische Industrie) scales which allow the precise identification of the phenological stages of tree tomato. Eight principal stages are described for germination, leaf development, formation of side shoots, stem elongation, inflorescence emergence, flowering, development of fruit, and ripening of fruit and seed. The basic (two-digit) scale is sufficiently precise for germination, stem elongation, and ripening of fruit and seed. However, for leaf development, formation of side shoots, inflorescence emergence, flowering, and development of fruit the extended (three-digit) scale is considered necessary for an adequate description. The description of the phenological stages is combined with illustrations for clarification. The tree tomato BBCH scale has been validated by characterizing 24 accessions of different varietal groups for traits of agronomic interest and evaluating the differences observed among accessions at specific BBCH developmental stages. The basic and extended BBCH scales represent a useful tool for the description and identification of phenological scales of tree tomato. These scales will be useful for the enhancement of this emerging fruit crop.

1. Introduction

Tree tomato (*Solanum betaceum* Cav., Solanaceae), also known as tamarillo, is an emerging exotic fruit crop native to the Andean region and cultivated in South America, as well as in other tropical and subtropical areas, like New Zealand, Australia, and India (Bohs, 1989; Carrillo-Perdomo et al., 2015; Samuels, 2015). The tree tomato fruits are fleshy and can be consumed in juices (its most common use), as a fresh fruit, cooked or processed in different ways (Bohs, 1989; Prohens and Nuez, 2000). Tree tomato fruits have a high content in ascorbic acid, provitamin A, carotenoids, and vitamin B_6, as well as a high antioxidant activity (Vasco et al., 2009; Acosta-Quezada et al., 2015; Espin et al., 2016), which is stimulating its demand in both local and overseas fruit markets (Carrillo-Perdomo et al., 2015).

The tree tomato plant is a small tree which, in commercial plantations, has a height of 2–4 m. The trees start bearing within 12–18 months of planting reaching a production peak at 3–4 years, which is maintained until the plant has 6–8 years; however, if the plant is well managed, it can live and produce until it reaches 8–12 years (Rotundo et al., 1981; National Research Council, 1989; Prohens and Nuez, 2000). The stem is typically divided in three (trifurcate) or two (bifurcate) main branches at a height of 1.1–1.8 m. The leaves are large (20–30 cm in length and 15–25 cm in width), simple, unlobed, with an ovate blade and evergreen. Stem leaves (produced at the younger stages of the plant) are considerably larger than the crown leaves (Acosta-Quezada et al., 2011). The inflorescence is branched (scorpioid cyme) with 10–50 flowers (Bohs, 1994). The flower is hermaphrodite and the anther morphology is very particular of the tree tomato and its wild relatives, which belong to *Solanum* section *Pachyphylla* (Bohs, 2007), presenting a dorsally gibbous anther connective that is joined to the two anther thecae.

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The tree tomato is diploid ($2n = 24$) and self-compatible (Pringle and Murray, 1991; Bohs, 1994). The fruit is ellipsoidal or ovoid, obtuse or acute at the apex, glabrous, yellow to orange, red, or purple, on occasion with darker longitudinal stripes (Acosta-Quezada et al., 2011; Bohs, 1994). Five cultivar groups, according to the fruit color and shape, are recognized (Acosta-Quezada et al., 2011, 2012): orange, orange pointed, purple, red, and red conical. Seeds are densely pubescent, and each fruit can present from a few (<10) to many (>350) seeds. Characterization with standardized morphological descriptors (Bioversity International et al., 2013) revealed large diversity within each cultivar group for descriptors related with plant height, size and shape leaf, inflorescence length, number of flowers, fruit size and weight, number of fruits/plant, and seeds per fruit (Acosta-Quezada et al., 2011). Despite the availability of these morphological descriptors, no internationally standardized tools exist in tree tomato for precisely determining the phenological stage, which is of great relevance for agronomic and botanical studies (Schwartz, 2013).

The "Biologische Bundesantalt, Bundessortenamt, and Chemische Industrie" (BBCH) numerical scale is a system for a uniform coding of phenologically similar growth stages of plants (Lancashire et al., 1991; Hack et al., 1992; Meier, 2001). The basic BBCH scale consists of a primary and a secondary scale, each of which is subdivided into 10 (0–9) clearly recognizable and distinguishable developmental phases. The primary scale defines the principal stages so that the entire developmental cycle of the plants is covered; the secondary scale is a subsequent division of the principal stages into 10 secondary development stages. An extended scale, which can provide a more detailed description can be established by including 10 mesostages (0–9), which are incorporated between the primary and secondary stages, resulting in a three-digit scale that provides a more detailed description (Meier, 2001).

The basic and extended BBCH scale have been successfully used in many crops, including some solanaceous crops native to the Andean region, like the economically important potato (*Solanum tuberosum* L.) and tomato (*Solanum lycopersicum* L.) (Feller et al., 1995; Hack et al., 1993; Meier et al., 2009), as well as emerging crops of this same region like pepino (*Solanum muricatum* Aiton) and cape gooseberry (*Physalis peruviana* L.) (Herraiz et al., 2015; Ramírez et al., 2013). However, up to now the BBCH scale has not been applied to the tree tomato, which presents some important differences with respect to these Solanaceous crops, like having a tree structure and a much longer period of development and cultivation (8–12 years). The purpose of this work is to establish a standardized BBCH phenological scale for tree tomato, and to validate it for evaluating differences in a set of accessions of this emerging fruit crop.

2. Material and methods

2.1. Plant material, cultivation and climatic conditions

Phenological observations were conducted by the authors since the 1990s in plants cultivated in the Andean region under commercial conditions and in experimental plots, as well as in experimental fields in Valencia (Spain). In particular, a detailed observation was conducted in a tree tomato morphological diversity trial initiated in 2007 in Ecuador. Data were obtained from a collection of 24 accessions of cultivated tree tomato belonging to five cultivar groups: orange, orange pointed, purple, red, and red conical originating in six countries (Acosta-Quezada et al., 2011). This trial was located at the UTPL farm (4°0′1.59″s and 79°10′48.46″W) in Loja, Ecuador at 2.160 m of altitude. This area corresponds to the low dry montane forest (bs-MB) formation (Holdridge, 1967), with 15.4 °C mean annual temperature and mean annual rainfall of 780 mm; the soil of the plot is clay loam. Plants were propagated from seed and the planting distance used was 2 × 2 m.

2.2. Tree tomato BBCH scale characteristics

A basic and an extended BBCH phenological scale specific to tree tomato were established according to the BBCH guidelines (Meier, 2001). The complete growth cycle of tree tomato has been subdivided into eight clearly recognizable principal growth stages, including germination (stage 0), stem and crown leaf development (stages 1a and 1b, respectively), formation of side shoots (stage 2), stem elongation (stage 3), inflorescence emergence (stage 5), flowering (stage 6), development of fruit and seed (stage 7), and ripening of fruit (stage 8). The development of harvestable vegetative plant parts or vegetatively propagated organs/booting (stage 4) is not applicable to tree tomato. The BBCH stage 9 was not considered as tree tomato is an evergreen that has no rest period and plantations are removed before plant senescence is evident. Given the particularities of the different development of stem and crown leaves of this species (Acosta-Quezada et al., 2011; Bioversity International et al., 2013), the tree tomato stage 1 (leaf development), has been subdivided depending on the type of leaves in consideration (stem vs. crown leaves) using the letters 'a' and 'b', respectively (e.g. 11a: first true leaf on stem fully unfolded, and 11b: first true leaf on crown fully unfolded).

The eight principal stages were subdivided into secondary stages ordered from 0 to 9, which can represent an ordinal number or a percentage (1 = 10%, 2 = 20%, etc.). These secondary stages describe specific time points or shorts intervals of development within each principal stage and are used as plant development stages that are precisely indicated, in contrast to the principal growth stages, which are longer developmental steps. The combination between the principal stage number and the secondary stage number results in the basic two digit BBCH scale (Meier, 2001). When the secondary stages are not well-defined with enough precision with the two digit scale, a mesostage from 0 to 9, is included between the principal and the secondary stage to create an additional subdivision generating the extended three-digit BBCH scale (Meier, 2001). For principal stages where the mesostage is not applicable and the extended BBCH scale is used, a 0 is used for the mesostage. The principal growth stages do need necessarily proceed in the strict numerical order of the digits defining the different stages of the basic or extended BBCH, but may also proceed in parallel. If two or more development stages take place in parallel, this can be indicated by using a diagonal stroke to indicate the different stages taking place simultaneously (e.g. 21/51) (Meier, 2001).

2.3. Validation of the tree tomato BBCH scale

The utility of the BBCH scale for the description and detection of differences among agronomically important traits at different precisely defined stages according to the BBCH scale were validated in 24 accessions from five cultivar groups using the Bioversity International et al. (2013) morphological and agronomical characterization descriptors. Traits evaluated included stem length (cm; stage 39 or 309), fruits per plant (stage 89 or 809), fruit length (cm, stage 81 or 801), fruit width (cm, stage 81 or 801) and fruit weight (g, stage 81 or 801), and fruit ripening (stage 85 or 805). For stem length, fruits per plant and fruit ripening after transplant 15 replicates (each plant was considered as a replicate) were considered, while for fruit length, width and weight 75 replicates (each corresponding to an individual fruit from a bulk of fruits harvested from the 15 individual plants evaluated) were measured. For each accession, the average and standard error (SE) were calculated for each trait.