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Selection of drought-tolerant tomato during the vegetative stage

Jessica Cardoso[1], Taizi Regina Silva[2], Antonio Carlos de Souza Abboud[3], Taciane Finatto[1], Leomar Guilherme Woyann[1], Thiago de Oliveira Vargas[1]

[1]Universidade Tecnológica Federal do Paraná – UTFPR, PR. [2]Universidade Federal de Viçosa – UFV, MG. [3]Universidade Federal Rural do Rio de Janeiro – UFRRJ, RJ. E-mail: thiagovargas@utfpr.edu.br

Abstract

Drought stress consists of a significant productivity constraint in tomatoes. Two contrasting crosses were performed to estimate physiological and morphological traits in response to drought stress during the vegetative stage, aiming to identify superior genotypes for drought tolerance. Two genotypes (GBT_2037 – sensitive drought-sensitive and GBT_2016 – intermediate drought-tolerant) were used as female parentals, and a commercial hybrid (drought tolerant) was used as a pollen source in both crosses: C1 (GBT_2037 × Commercial hybrid) and C2 (GBT_2016 × Commercial hybrid). The populations of parentals (P), the first generation of descendants (F_1), backcrosses (BC), and the second generation of self-pollination (F_2) were exposed to drought stress for 20 days when they were analyzed: physiological traits (relative water content of leaves, proline, and relative chlorophyll content) and morphological (plant height, stem diameter, number of leaves, fresh and dry matter of roots and shoot and classification by wilt scale). The means of chlorophyll, root/shoot ratio, and water content in leaves for the F_2 generation of C2 were higher than C1, indicating that C2 resulted in plants with greater capacity to maintain turgor under conditions of water stress and presented minor damage to the photosynthetic structures, consequently showing greater tolerance to drought stress.

Keywords: abiotic stress; genotypes; *Solanum lycopersicum* L.

Seleção de tomate tolerante à seca durante fase vegetativa

Resumo

O estresse hídrico consiste em uma importante restrição à produtividade do tomateiro. Dois cruzamentos contrastantes foram realizados para estimar características fisiológicas e morfológicas envolvidas na resposta ao estresse hídrico durante a fase vegetativa, visando identificar genótipos superiores para tolerância à seca. Dois genótipos (GBT_2037 – sensível à seca e GBT_2016 – intermediário tolerante à seca) foram utilizadas como parentais femininos e um híbrido comercial (tolerante à seca) foi usado como fonte de pólen em ambos os cruzamentos: C1 (GBT_2037 × Híbrido comercial) e C2 (GBT_2016 × Comercial híbrido). As populações de parentais (P), primeira geração de descendentes (F1), retrocruzamentos (BC) e segunda geração de autopolinização (F2) foram expostas ao estresse hídrico durante 20 dias, quando foram analisadas: características fisiológicas (conteúdo relativo de água das folhas, prolina e teor relativo de clorofila) e morfológicos (altura da planta, diâmetro do caule, número de folhas, matéria fresca e seca de raízes e parte aérea e classificação por nivel de murcha). As médias de clorofila, razão raiz/parte aérea e teor de água nas folhas para a geração F2 de C2 foram superiores a C1, indicando que C2 resultou em plantas com maior capacidade de manter o turgor sob condições de estresse hídrico e apresentou menos danos nas estruturas fotossintéticas, consequentemente apresentando maior tolerância ao estresse hídrico.

Palavras-chave: estresse abiótico; genótipos; *Solanum lycopersicum* L.

Introduction

Tomato (*Solanum lycopersicum* L.) is one of the most widespread crops worldwide (SALIM *et al.,* 2018; YAMAMOTO *et al.,* 2018). Although economically important, susceptibility to several abiotic stresses, such as drought, considerably narrows its development (ÇELIK *et al.,* 2017).

Climate change is already a global reality, and extreme droughts, intense heat, and floods occur with increasing frequency and intensity. These factors can result in significant and sudden losses in the agricultural sector, resulting in low productivity, which will increase food prices and reduce the livelihoods of many families in the coming years (IPCC, 2022). In the case of tomatoes, wild species generally adapt to different soil and climatic conditions (DEMPEWOLF *et al*., 2017; OLIVIERI *et al*., 2020; GASPARINI *et al*., 2021). These adaptations are helpful for the development of more tolerant genetic constitutions to abiotic stresses (HALIŃSKI *et al.,* 2015; JORDANOVSKA *et al*., 2020).

The ability of a plant to maintain higher water content in tissues in dry conditions is the result of adaptive characteristics that involve the reduction of water loss and its optimization in absorption (BASU *et al*., 2016; DE ABREU *et al*., 2019; IQBAL *et al*., 2020). When subjected to water stress, Plants exhibit changes in metabolism and growth, depending on the ability to tolerate the duration and level of stress to which they are subjected (PATANÈ *et al*., 2016; SELEIMAN *et al*., 2021; SACHDEV *et al*., 2021).

There are several characteristics evaluated in studies looking for drought-tolerant tomato genotypes. Generally, the evaluations considered are related to the plant's ability to maintain water in the leaves under stress conditions or to reduce the consequences of this stress through specialized amino acids. Characteristics such as the accumulation of solutes (especially proline), the relative water content, and the concentration of chlorophyll in the leaves can often be observed in studies looking for tomato genotypes tolerant to this condition (PATANÈ *et al*., 2016; LANDI *et al*., 2017; ARTEAGA *et al*., 2020).

When exposed to water stress, plants also show reduced growth and development, as they need energy, water, and nutrients for good growth (CRAMER *et al*., 2013; SELEIMAN *et al*., 2021). Thus, the measurement of root and shoot growth and the relationship between them are also essential characteristics to consider a good plant establishment in these conditions and may be helpful in the selection of genotypes tolerant to this condition (BASU *et al*., 2016; ÇELIK *et al*. 2017).

Conventional breeding has evolved over the years, becoming a tool capable of improving crop performance while developing more nutritious and safer foods for the population; this process is based on decision-making, for example, choosing the best parents and the most promising progeny. Plant breeding benefits from the ability to create large populations, which will be discarded to select from a few individual plants that present desired characteristics to advance future generations. This ability to choose a few individuals from large populations is critical for plant breeding and is applied during many stages (KAISER *et al*., 2020).

In the case of drought tolerance or traditional breeding, the method allows for identifying genetic variability for tolerance between genotypes and introducing this characteristic with different forms of crossbreeding between lines with features of interest. Studies on traditional breeding under drought stress conditions in tomatoes are scarce. Several genes with additive effects control the response to drought stress, making it hard to identify traits defining the genotypes with higher tolerance to stress (ASHRAF, 2010; BARIK *et al*., 2019).

Therefore, studying physiological and morphological traits and tolerance mechanisms in tomato genotypes submitted to drought stress is essential to considering potential progenies for breeding programs (TAPIA *et al*., 2016; ÇELIK *et al*., 2017).

The phenotypic analysis of genotypes in the initial phase of development (seedlings) can be an excellent strategy within traditional breeding because it reduces the time and the area destined for these evaluations, being fast and easy to evaluate (ABREU *et al*., 2019). The present study estimated morphological and physiological characteristics in the vegetative tomato stage of populations obtained from two crosses and their respective parents under water stress conditions. This assessment identified possible drought-tolerant genotypes from morphological and physiological traits in new generations.

Materials and methods

Two genotypes (GBT_2037 – drought-sensitive and GBT_2016 – intermediate drought-tolerant) were used as female parentals and a commercial hybrid (drought tolerant). Two simple crosses between tomato genotypes were performed: accession GBT_2037 × commercial hybrid (C1) and GBT_2016 × commercial hybrid (C2). A general description of the plant material is shown in Table 1.

Table 1. Description of main characteristics related to female parents (GBT_2037 and GBT_2016) and the male parent, the Commercial hybrid.

Parent	Characteristics
GBT_2037	Open-pollinated access with red fruits and plurilocular, indeterminate growth habit, predominantly cylindrical to cordiform in shape, stable yield, with good adaptation to hot climates and high temperatures.
GBT_2016	Open-pollinated access with red fruits and plurilocular, indeterminate growth habit, slightly flattened shape, stable yield, and adapted to hot climates.
Commercial hybrid	Present indeterminate growth, good yield potential, medium-to-large, round, firm red fruits, high resistance to mosaic virus, *Verticillium* wilt and *Fusarium* wilt, drought tolerance, and intermediate resistance to Tomato spotted wilt virus and nematode *Meloidogyne.*

Evaluations related to drought conditions were carried out using 100 plants from the F_2 generation, eight plants of each parental (P_1 and P_2), eight plants of each backcross (BC_1 and BC_1), and 15 plants for each F_1 generation, totalizing 147 plants for the six populations of each cross (294 plants in total), using a completely randomized design. To originate the F2 generations, one seed was selected from each of the 100 F1 plants from each cross, totaling 200 plants.

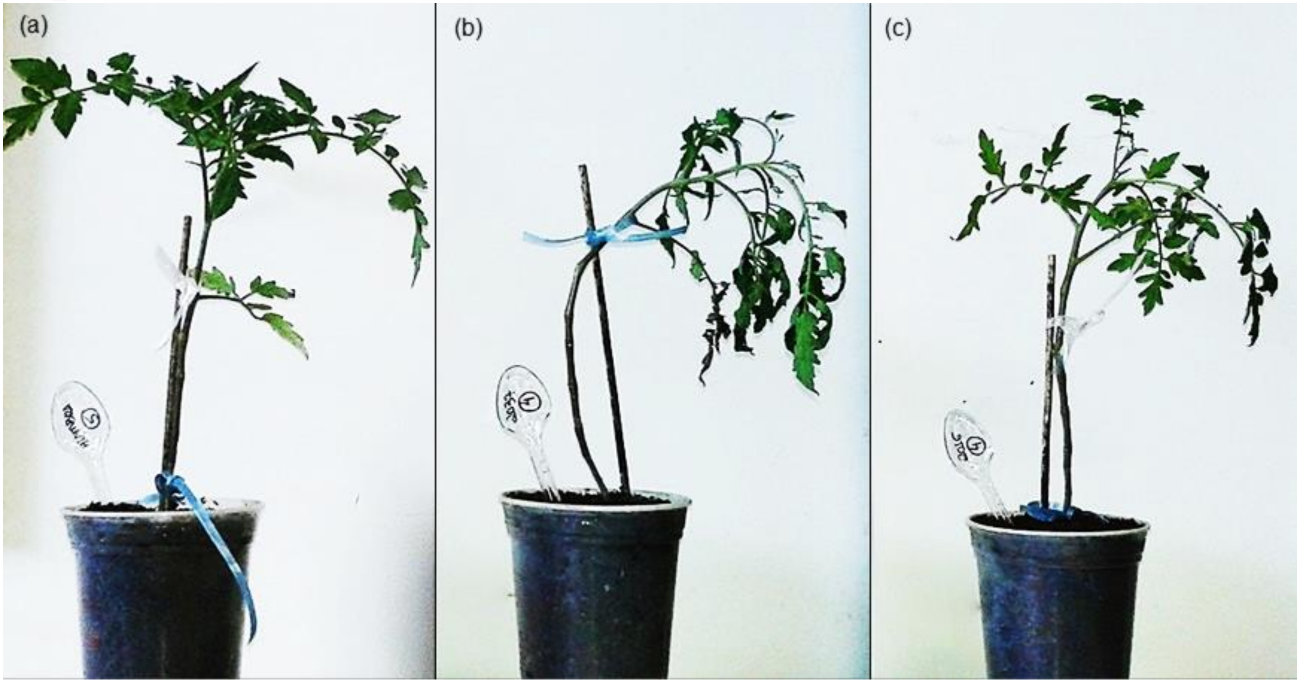
Seeds were sown in multi-cell seedling trays filled with sterilized commercial organic compost substrate. Irrigation occurred daily for the first 20 days. Plants were then transferred to 700 mL pots filled with a 3:1 (v/v) mixture of soil and poultry manure (both sieved at 4 mm diameter). Plants were kept in a plastic greenhouse with a mean temperature of 26 °C ± two °C daily, 20 °C ± two °C nightly, and 60% relative humidity. The substrate was kept at 80% of field capacity (FC) (YANG *et al.*, 2017) for 65 days to ensure plant development. FC was determined gravimetrically (DOBRIYAL *et al.,* 2012), using the dry and wet weight of soil samples from reference containers identical to those used in the experiment and under the same temperature and humidity conditions.

After 65 days in a plastic greenhouse with regular irrigation, when the plants presented three true leaves, they were then submitted to drought stress for 20 days, ceasing daily watering until they reached 25% of FC, in controlled chambers (fitotron) with the following features: temperature of 26 °C maximum, 25 °C mean, and 22 °C minimum; photoperiod of 14/10h (day/night); the light intensity of 300 ± 20 µ mol m^{-2} s^{-1}, and relative humidity 60 %, being the plants dispossessed in an entirely unexpected way.

Morphological and physiological evaluations were performed at the end of the drought stress period. The end of the stress period was determined when symptoms in the parents started.

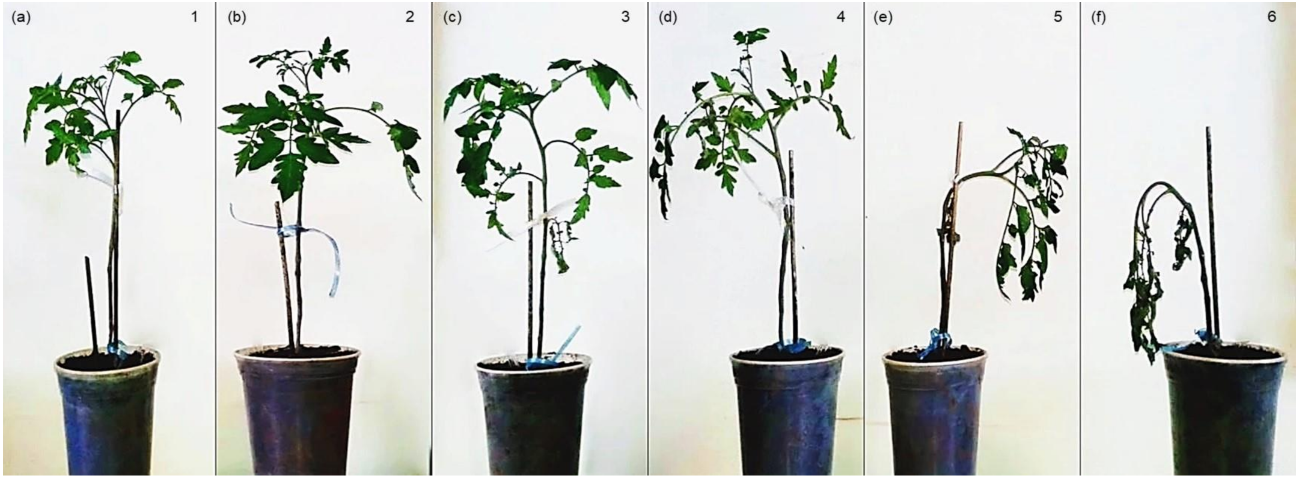
The symptoms become evident no later than the 20th day after the onset of drought in some genotypes. These symptoms consist of wild changes in the color of the leaves and leaf abscission (Figure 1).

Figure 1. Performance of the parentals after 20 days of drought stress, achieving 20% of field capacity in the vegetative stage. **a)** Commercial hybrid – drought-tolerant, **b)** GBT_2037 – variety drought-sensitive, **c)** GBT_2016 - variety intermediate drought tolerant.



A scale from 1 to 6 was used to assess the wilt level (WL) on tomato plants submitted to drought stress for 20 days (25% of FC) (Figure 2). The WL scale used was an adaptation of Banik et al. (2016) proposed, who worked with potatoes.

Figure 2. Grading (1 to 6 from left to right) of wilt level intensities in tomato plants submitted to water scarcity for 20 days (25% of field capacity). Meaning: **a)** no wilted leaves, **b)** 25% wilted leaves, **c)** 50% wilted leaves, **d)** 75% wilted leaves, **e)** 100% wilted leaves, and **f)** 100% wilted leaves and a 100% wilt stem with slightly brown coloration.



Plant height (PH) was measured from the apical portion to the stem base. Stem diameter (SD) was measured with a digital caliper, 2 cm above the plant's first collar. The number of leaves (NL) was determined by counting all plant leaves. Roots and shoots were separated and quantified for fresh matter immediately after harvesting, then hot air-dried in the oven under 60 °C until a constant mass was achieved. After it, the dry weight of root (DMR), dry weight of shoot (DMS), and shoot and root ratio (DMR/DMS) were obtained.

The last fully expanded leaf from the top of each plant was used to quantify the following traits: leaf fresh matter (FW), turgid leaf weight (TW), and leaf dry matter (DW). These traits were used to determine the relative water content (RWC) of leaves, according to the methodology proposed by Zhou et al. (2017), where:

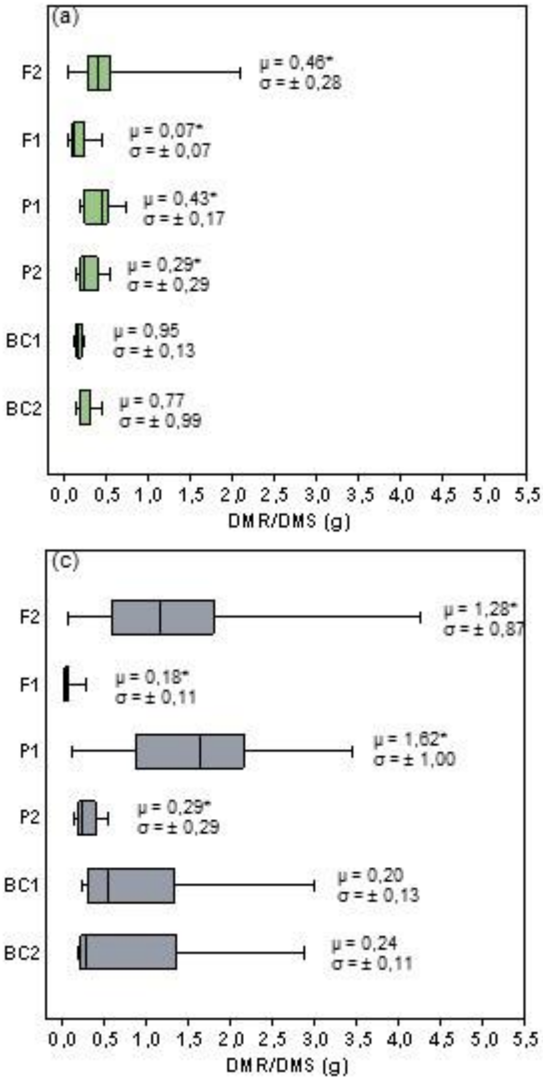
Proline (PROL) levels in leaves were obtained according to Bates (1973). The relative chlorophyll content (CHL) was performed using the first expanded leaf from the base of each plant (Zhou *et al*., 2017), using a ClorofiLOG portable chlorophyll meter, model CFL 1030 (FALKER, Porto Alegre/Brazil).

The determination of the number of stomata (SNL) was performed according to Mishra et al. (2012). The counting of the number of stomata was performed with an optical light microscope with a magnification of 100x equipped with a digital camera. Images were analyzed using Micrometrics™ SE Premium software. Three non-overlapping photographs were taken for each slide, with stomatal density determined by directly counting the number of stomata per image (SUN *et al*., 2014). For each cross, the first generation of descendants (F_1), the second generation of descendants (F_2), and the parentals and backcrosses (BC_1 and BC_2) were analyzed. For better viewing of the results, boxplots were generated using PAST software, version 3.14 (HAMMER *et al*., 2001). The student's t-test was performed with the Minitab software, version 19.2020.1, to verify statistically significant variation between the means of the crossings ($p<0,1$).

Results and discussion

The comparison of means indicated higher mean values of RWC for the parent considered tolerant and, therefore, greater capacity to maintain tissue turgor during the dry period (Figure 3). This genotype also had a higher CHL index and lower averages for WL, SNL, and PROL. The sensitive parent increased the DMR/DMS ratio, showing intermediate levels of PROL and the weakest indices of CHL (Figure 3 and Figure 4). In C2 (moderately tolerant x tolerant), population F_1 had the highest levels of CHL and the highest values for PROL, while population F_2 had the highest DMR/DMS.

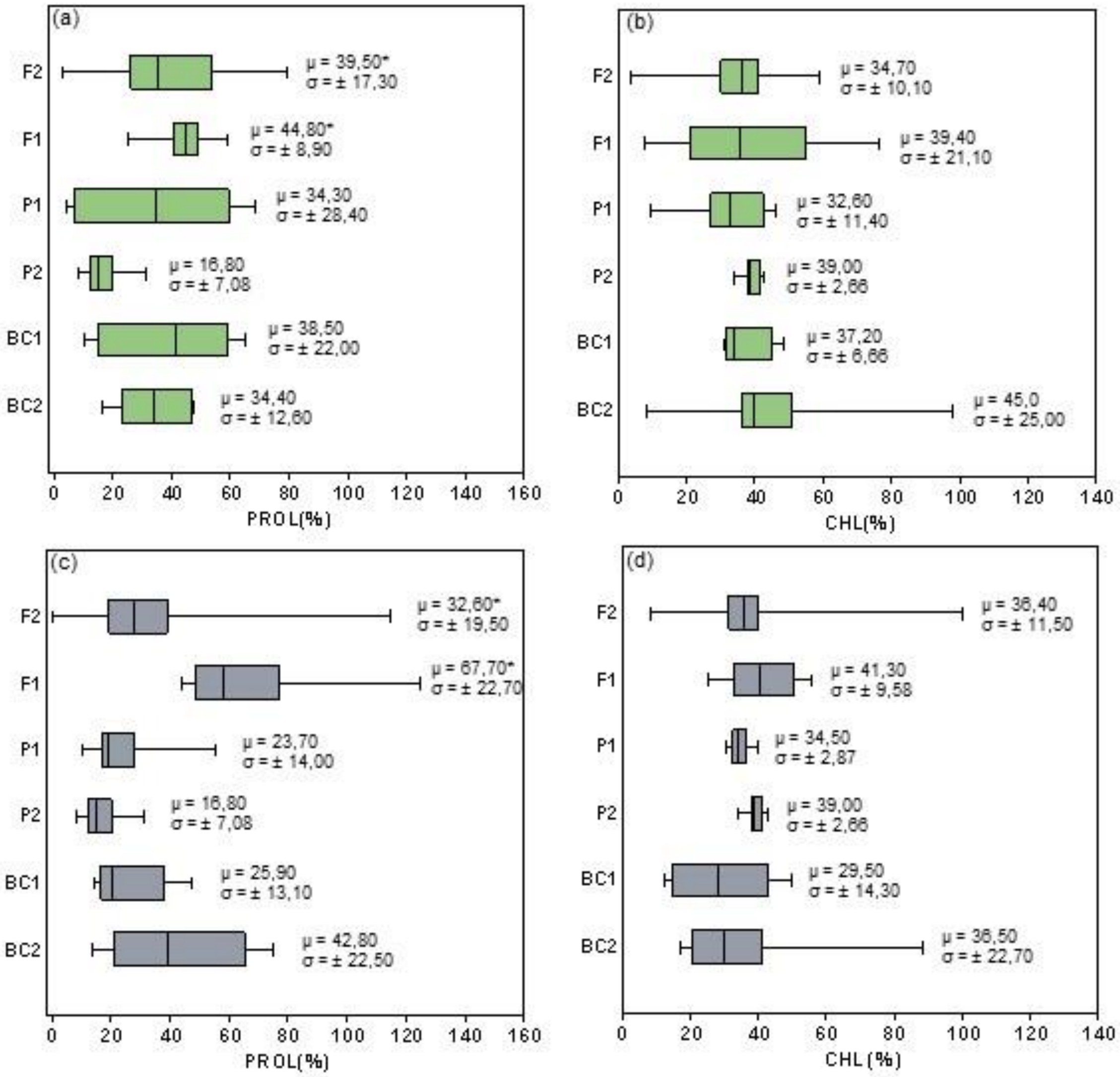
Figure 3. Box-plot graphs for generations F_1, F_2, parentals (P_1 and P_2), and backcross (BC_1 and BC_2) for C1 (GBT_2037 × Commercial hybrid) (a and b) and C2 and GBT_2016 × Commercial hybrid) (c and d). DMR/DMS - shoot and root ratio (a and c), RWC - relative water content (b and d), µ - means, and σ - standard deviation. The asterisk (*) indicates a significant difference (> 0.05) between the crosses obtained by the student's t-test.



Both crosses generated F_1 and F_2 populations with a CHLOR index and PROL accumulation greater than the parental mean (Figure 4). The F_1 of the contrasting cross (tolerant x sensitive) resulted in a higher frequency of individuals with visible dehydration of the leaves. Both crosses resulted in higher RWC and CHL values in F_1 than in F_2. Backcrossing of BC_1 with the recurrent tolerant parental resulted in the highest CHLOR indices.

Considering the average of two backcrosses for both the crosses (C1 and C2), BC1 and BC2 will show similarity as P1 and P2, respectively, for all the evaluated traits, except the DMR/DMS for BC1 and RWC for BC2, where possibly genes with undesirable characteristics may have been expressed.

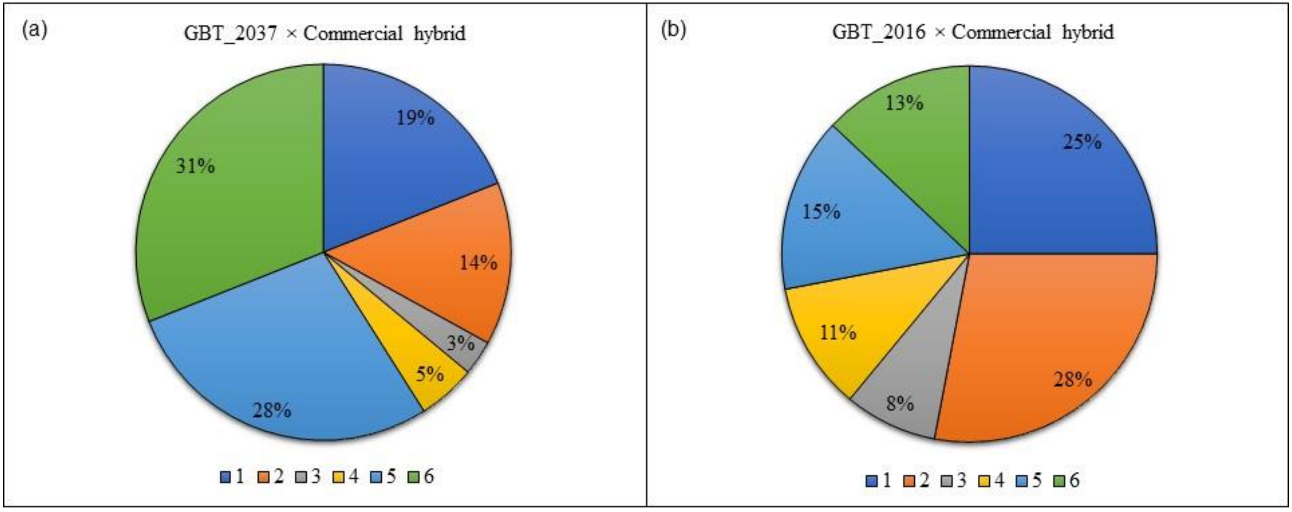
Figure 4. Box-plot graphs for generations F_1, F_2, parentals (P_1 and P_2), and backcross (BC_1 and BC_2) for C1 (GBT_2037 × Commercial hybrid) (a and b) and C2 and GBT_2016 × Commercial hybrid) (c and d). PROL - proline (a and c), CHL - relative chlorophyll content (b and d), µ - means, and σ - standard deviation. The asterisk (*) indicates a significant difference (> 0.05) between the crosses obtained by the student's t-test.



The SNL indicated that the parentals (P_1 and P_2) did not show significantly contrasting differences, with 60.13, 73.38, and 66.17 for the parents GBT_2037, GBT_2016, and the commercial hybrid, respectively, providing little variability between generations.

The mean values of SD and NL were higher for C1 in generation F_2, whereas PH and WL were higher for C2. The WL was determined in F_2 genotypes following the scale shown in Figure 2. The highest levels were found in C1, with 31% of genotypes at level 6, 28% at level 5, and 19% at level 1 (Figure 5). Otherwise, C2 showed only 13% genotypes at level five, 25% at level 1, and 28% at level 2, indicating a higher chance of finding tolerant genotypes in C2 than in C1.

Figure 5. A piechart for the frequency distribution of wilt level (WL) of the F_2 generation of two tomato crosses. a) cross C1 (GBT_2037 × Commercial hybrid), and b) cross C2 (GBT_2016 × Commercial hybrid). Where: 1 = no wilted leaves, 2 = 25% wilted leaves, 3 = 50% wilted leaves, 4 = 75% wilted leaves, 5 = 100% wilted leaves and 6 = 100% wilted leaves, and 100% wilt stem with slightly brown coloration.



The box plots for physiological traits, including F1, F2, parentals, and backcross generations, can be visualized in Figures 3 and Figure 4. For DMR/DMS ratio, the F_2 ages were symmetrically distributed concerning the median for both crosses, with the most significant data variability found for C1. For PROL and CHL, C1 also presented a higher data variability compared to C2. Otherwise, for RWC, C2 showed a higher data variability than C1.

The box-plot for F_2 generations for RWC, PROL, and CHL are shown in Figure 3 and Fig 4. The mean and variability of C1 were lower than C2 for the RWC and CHL variables, while the PROL mean was higher. The C2 presented data symmetry concerning the median for all variables except for PROL, where a positive asymmetry occurred. C1 showed data symmetry only for RWC and positive and negative symmetry for PROL and CHL.

The generation F_1 referring to C1, presented a higher mean concerning the generation F_2 for all variables and intermediate values to parental ones. F_2 generation showed intermediate matters relating to parentals, except for the RWC, in which the mean was identical to P_1. Data regarding C2 follow this same trend line, with the F_2 generation mean comparable to P_1 parental for RWC and intermediate to other variables.

The C2 population presented the highest values for SD and NF, indicating their greater leaf expansion capacity under drought stress conditions. However, the highest F_2 means for DMR/DMS were found in the population obtained from C1, indicating a higher root formation under water stress conditions. Also, the WL average was higher for C1, indicating that these genotypes show greater capacity to form roots under drought conditions; this trait was insufficient to keep plants turgid under these conditions, as evidenced by the lower RWC of this generation.

Although root growth can indicate better plant efficiency under drought conditions, as it allows water absorption in greater soil depths (BASU *et al*., 2016; LYNCH *et al*., 2021; CALLEJA-CABRERA *et al*., 2020), this characteristic is not synonymous with greater tolerance for the species in all conditions. An example is the shallower soils, where water is not available at great depths to be absorbed (VADEZ, 2014).

This fact may have been a factor that contributed to the results found in the present study since the plants were grown in pots, which limits the exploitation of water by the roots. Together with the RWC and CHL values, this characteristic indicated a greater efficiency of the C2 in surviving under drought stress conditions even with lower root mass values. In addition, other root characteristics are involved in the water uptake process by the roots, such as the presence of root hairs, which are responsible for the significant increase in the water absorption area by the sources and the hydraulic conductivity of the root (VADEZ, 2014; BASIRAT *et al*., 2019; LYNCH et al., 2021).

Mean RWC indexes were higher for C2, suggesting greater drought tolerance when compared to C1. RWC can identify inadequate water absorption in drought-prone plants. These plants tend to lose water due to metabolic processes, and they may resort to strategies to conserve water when dealing with increasing stress (ÇELIK *et al.*, 2017).

The average value found for the generation F_2 obtained from the C1 concerning PROL concentration was higher than that found by C2. Proline has an essential role in antioxidant defense: stabilizing enzymes and proteins; preventing damage caused by excessive levels of reactive oxygen species (ROS); helping to maintain the integrity of cell membranes, and, as well as the metabolite; assisting the water in balance (HOSSAIN *et al.*, 2014; ILYAS *et al.*, 2021). This fact can also be observed in studies by Patanè *et al.* (2016), Landi *et al.* (2017), and Dipp *et al.* (2017).

Although PROL is essential in the plant's defense under water scarcity conditions, controversy over whether its accumulation can be considered an adaptive response or only a symptom caused by stress (MONTESINOS-PEREIRA *et al.*, 2014). A lower ability to maintain turgor under stress conditions for C1 may be occurring. The highest PROL mean was associated with a lower mean RWC in the leaves, suggesting a deficiency in the osmotic adjustment for this population. If that happened, it did not occur to a great extent in other parameters.

The levels of CHL for generation F_2 obtained from C1 presented a lower mean if compared to F_2 from C2. Generally, higher CHL content is related to more inadequate damages to photosynthetic structures and may indicate higher tolerance of plants when subjected to severe drought (AGHAIE *et al.*, 2018; ÇELIK *et al.*, 2017). These results may show a higher oxidative stress index for the genotypes belonging to C1, suggesting lower resistance to water scarcity, because when submitted to abiotic stresses, plants tend to trigger ROS synthesis, negatively affecting the metabolism and inducing oxidation of photosynthetic pigments, including CHL (TRIPATHY; OELMÜLLER, 2012; AHANGER *et al.*, 2017; SHARMA *et al.*, 2020).

This fact can be confirmed when we observe the behavior of the parents, where the parent considered tolerant (commercial hybrid) had the highest CHL index, followed by the moderately resistant (GTB_2016) and the sensitive (GBT_2037), which contributed to the F_2 of C2 had higher means for this variable. These results contributed to investigating traits involved in tomatoes' tolerance when subjected to drought. However, further studies should be carried out with this approach since these characteristics and their possible use in selecting new generations of the crop are still poorly understood. They may show variation when considering the genotype, methodology, and level of stress they are subjected to. Therefore, it is necessary to carry out further studies at different sites, climates, and crop stages to validate the efficiency of these genotypes subjected to drought conditions.

While the work is focused on the F2 generations, the F1 ages show significant variability for some physiological characteristics (CHL, PROL, and RWC), suggesting that not all the variability observed is due to environmental causes, resulting in combinations of genes that may become interesting for the improvement, being this more significant variability of the species important in the adaptation of the plant in extreme conditions.

Conclusions

The cross between GBT_2016 and Commercial hybrid resulted in plants' ability to maintain turgor under drought stress conditions, mainly due to their higher leaf expansion capacity, relative water content, and chlorophyll content in the leaves.

Genetic variability regarding drought stress tolerance was found in the studied F2 generations of tomato plants. The present study will allow future studies to be carried out using controlled self-fertilization of potential genotypes to obtain possible lineages tolerant to drought.

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