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Agronomic performance of tomato hybrids and inbred lines using vegetation indexes

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ABSTRACT

Image phenotyping presents great potential for field experiment evaluations in tomato crop. Validating this method for tomato plants is important to reduce costs and time. Thus, the objective of the present study is to investigate the agronomic performance of tomato hybrids and inbred lines using vegetation index. A randomized block design with three replications was used. A total of36 experimental hybrids and 9 inbred lines were evaluated, in addition to the recurrent genitor UFU-57 and a commercial hybrid, culminating in 47 treatments. During the experiment, average weight, transverse and longitudinal diameter, pulp thickness, number of lobules, soluble solids, β-carotene and lycopene concentrations were evaluated. Moreover, the vegetative development of plants was analyzed utilizing vegetation index, obtained using remotely piloted aircraft. The data were analyzed using mean test and multivariate analysis. The results showed that vegetation index can distinguish hybrids from inbred lines and can be used to evaluate tomato germplasm in future phenotyping.

Keywords: *Solanum lycopersicum* L., food sustainability, genetic dissimilarity, high-throughput phenotyping, image analysis.

RESUMO

Desempenho agronômico de híbridos e linhagens de tomateiro a partir de índices de vegetação

O uso da fenotipagem por imagens apresenta alto potencial para avaliação de experimentos na cultura do tomateiro. Validar a aplicação desse método é importante par reduzir custos e tempo. Assim, a pesquisa teve como objetivo investigar o desempenho agronômico de híbridos e linhagens de tomateiro a partir de índices de vegetação. Foi utilizado o delineamento em blocos casualizados com três repetições. Foram avaliados 36 híbridos experimentais e 9 linhagens, além do genitor recorrente UFU-57 e um híbrido comercial, totalizando 47 tratamentos. Foram avaliados o peso médio, diâmetro transversal e longitudinal, espessura da polpa, número de lóculos, teores de sólidos solúveis, β-caroteno e licopeno. Além disso, analisou-se o desenvolvimento vegetativo da planta por meio de índices de vegetação obtidos com o suporte de uma aeronave e remotamente pilotada. Os dados foram analisados por meio de teste de média e análise multivariada e demonstraram que índices de vegetação podem ser capazes de distinguir linhagens dos híbridos e que o uso de imagens, para avaliação do germoplasma de tomateiro, pode auxiliar em futuras fenotipagens.

Palavras-chave: *Solanum lycopersicum* L., sustentabilidade alimentar, fenotipagem de alto desempenho, análise de imagem.

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Tomato (*Solanum lycopersicum* L.) is one of the world's most widely grown and consumed vegetables representing great importance to the Brazilian economy. Brazil is the ninth largest producer in the world (3.6 million tons), corresponding to an area of more than 50 thousand hectares (FAOSTAT, 2023). Tomatoes are classified into salad, saladette, Santa Cruz, industrial, and special (grape, cherry and others) and can present different growth habits, directly affecting its crop system (Finzi *et al*., 2017). Despite their potential, tomato plants are highly vulnerable to various biotic and abiotic stresses. In this context, repeated evaluations of genotypes in field experiments are necessary, resulting in a greater demand for time and resources (Gomes *et al*., 2021).

Fruit quality has also been constantly evaluated for its health benefits and as raw material for the industry (Pereira *et al*., 2020). Therefore, tomato breeding programs aim to obtain cultivars that, in addition to good agronomic performance, present fruit quality (Oliveira *et al.*, 2022).

Image phenotyping has been widely used in vegetables such as lettuce (Maciel *et al.*, 2020; Clemente *et al.*, 2021) and summer squash (Beloti *et al.*, 2020), due to the need of trialing optimization (time and resources). However, the efficiency of using vegetation index for tomatoes is unknown.

Some studies report that this technique is advantageous since it offers high precision and low cost in acquiring information throughout the crop cycle (Herzig *et al.*, 2021; Coelho *et al.*, 2024). The calculation of vegetation index, obtained by measuring the radiation reflected by the plants, is one of the possible applications of this technique (Clemente *et al.*, 2021). In order to maximize the results, the experiments should be strategically planned and, when possible, include lines (inbreeding) *versus* hybrids (heterosis) to validate vegetation index (Silva *et al*., 2022).

Given the potential of using imaging techniques for plant phenotyping in several species and considering the scarcity of data in tomato breeding, more information is required. Thus, the objective of this study is to evaluate the agronomic performance of tomato hybrids and inbred lines using vegetation index.

MATERIAL AND METHODS

The experiment was conducted in the field at the Experimental Vegetable Station of the Federal University of Uberlândia (UFU), located in the municipality of Monte Carmelo, Minas Gerais State (18°42’43”S, 47°29’56”W; 873 m altitude).

The germplasm used in this study is part of the tomato breeding program of UFU. In 2016, an interspecific cross was made using UFU-57 (*Solanum lycopersicum* L.) as the recurrent genitor and the wild access LA-716 (*Solanum pennellii*) as the donor genitor. The pre-commercial inbred lines UFU-57 is a salad type, has a determinate growth habit, and presents favorable characteristics, especially large and vigorous fruits. The wild access has an indeterminate growth habit and is rich in a secondary compound (allelochemical) that results in a broad spectrum of resistance against pest attacks. After obtaining the F_1 seeds, we proceeded with two backcrosses and four successive self-fertilizations, resulting in nine homozygous inbred lines. In 2018, we performed the hybridization between the lines, and 36 experimental hybrids were obtained.

In December 2019, 47 genotypes with determinate growth habit were sown: 9 inbred lines, 36 experimental hybrids, the recurrent genitor UFU-57, and one commercial hybrid (cv. Vitalino 32).

Seeds were sown in polyethylene trays, containing 200 cells filled with coconut fiber substrate. After sowing, the trays were relocated to a greenhouse, where they remained for 35 days until the seedlings were ready to be transplanted to the field.

Plants were transplanted in January 2020, using a randomized block design with three replications (Figure 1).

The experimental plot consisted of five plants, 40 cm apart, arranged in a single row. Agricultural treatments were performed as recommended for the crop.

Plants were harvested 135 days after sowing (DAS). Since these plants have a determinate growth habit, manual harvesting was performed only once. All fruits of the plot were harvested, counted, and weighed to determine the mean fruit weight (MFW) and production per plant (PP). Fruits were submitted to the following agronomic evaluations: transverse diameter (TD), measured with a graduated ruler at the cross-section of the cut fruit (cm); longitudinal diameter (LD), measured with a graduated ruler from the pedicel scar to the apical region of the fruit (cm); number of locules (NL), determined by direct counting of the locules in the fruit (locus per fruit); pulp thickness (PT), measured with a graduated ruler and determined by the greatest distance from the fruit mesocarp (cm); and soluble solids concentration (SS), expressed as °Brix at 26°C, analyzed using a portable digital refractometer (Atago PAL-1 3810) (Finzi *et al.*, 2017).

After the agronomic evaluations, we analyzed the nutritional quality of the fruits: lycopene content (LC), obtained by reading in a Thermo Scientific spectrophotometer (Multiskan FC) at 470 nm; and β-carotene content (BC), obtained by reading in a UV-160 Visible Spectrophotometer (Shimadzu) at 450 nm.

Besides the agronomic evaluations, three flights were performed during plant development (15, 45, and 60 days after planting) at a 25 m height, using a remotely piloted aircraft (RPA) (Phantom 4 Advanced®) equipped with two optical sensors. The images were captured using an RGB camera (DJI Phantom 4 Advanced® Camera) with a 12-megapixel resolution. The image collection dimension was 4864 × 3648 pixels, with a longitudinal and lateral overlap of 75% and spatial resolution of 1.5 cm/pixel. The images were captured at noon, the period with greater solar radiation uniformity on the earth’s surface, to minimize shadow effects. The methodological steps for quantifying leaf pigments, image processing, and data analysis are presented in Figure 1. The images obtained during the flights were processed by calculating three vegetation indexes (Chart 1).

Data underwent analysis of variance using the F test ($p<0.05$). The means were compared by the Scott-Knott test ($p<0.05$) and, subsequently, multivariate analyses of genetic dissimilarity were performed using the generalized Mahalanobis distance (Dii'2). Genetic dissimilarity was represented using a dendrogram obtained by the hierarchical Unweighted Pair-Group Method Using Arithmetic Averages (UPGMA) and Tocher's optimization method. Grouping validation by the UPGMA method was determined by the Cophenetic Correlation Coefficient (CCC) (Mantel, 1967). The relative contribution of quantitative characters was calculated according to Singh's (1981) criteria. Contrasts of interest were performed employing the Scheffé test ($p<0.05$ and 0.01). The statistical analyses were performed in the GENES software (Cruz, 2013).

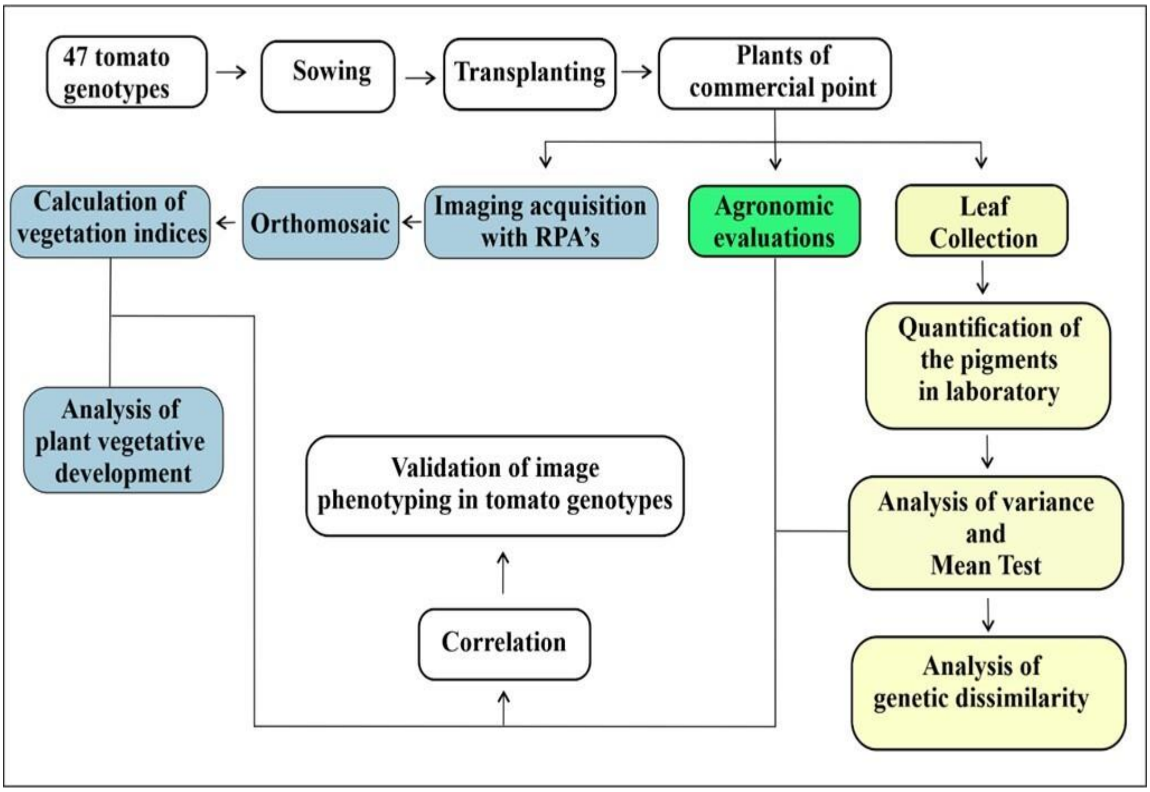

Figure 1. Flowchart of the imaging acquisition and processing, quantification of leaf pigments, and data analysis steps in tomato genotypes. Monte Carmelo, UFU, 2020.

Chart 1. Characteristics of the vegetation indices calculated for this study. Monte Carmelo, UFU, 2020.

Vegetation indices	Equations	References
Chlorophyll Vegetation Index (CVI)	$\rho n^{X} \rho r/\rho g^{2}$	Vincini *et al*., 2008
Green Normalized Difference Vegetation Index (GNDVI)	$(\rho n-\rho g)/(\rho n+\rho g)$	Gitelson *et al*., 1996
Soil Adjusted Vegetation Index (SAVI)	$(1 + 0.5)(\rho n - \rho r)/(\rho n + \rho r + 0.5)$	Huete, 1998

ρn = near-infrared band reflectance; ρr = red band reflectance; ρg = green band reflectance; ρb = blue band reflectance; ρr = defined by the equation ρr-(ρb- ρr).

RESULTS AND DISCUSSION

Tomato genotypes differed among themselves (F test, $p<0.05$) in all variables analyzed, except for PT (Table 1).

Regarding production per plant (PP), inbred line 8 and experimental hybrids 10, 22, 42, 43, and 44 highlighted, being superior to the commercial hybrid Vitalino 32 (Dunnett at 0.05 significance). The other genotypes analyzed were similar to UFU-57. For MFW, the experimental hybrids 17, 26, and 35 stood out compared to UFU-57. Inbred lines 5, 6, 7, 8, and 9 and hybrids 10, 11, 12, 13, 14, 15, 16, 18, 19, 20, 21, 22, 23, 24, 25, 27, 28, 29, 30, 31, 32, 33, 34, 36, 37, 38, 39, 40, 41, 42, 43, 44, and 45 showed an increase of 46 and 91 to 117.46%, respectively, in MFW. Furthermore they were also superior to Vitalino 32 (Table 1).

Table 1. Comparison of means among tomato genotypes (inbred lines and hybrids), for agronomic characteristics and fruit quality. Monte Carmelo, University Federal de Uberlândia, 2020.

ID	Genotypes	PP (Kg/plant)	MFW (g)	TD (cm)	LD (cm)	NL	PT (cm)	SS (ºBrix)	LC (mg/100g)	BC (mg/100g)
1	Inbred line UFU-2413	0.35 b	86.7 b	4.2 b*#	5.5 b*	4.9 a*	0.54 a	3.4 b	1.6 b	1.1 b*
2	Inbred line UFU-4412	0.33 b	86.7 b	4.2 b*#	5.5 b*	5.1 a*	0.43 a	3.1 b	1.8 b	2.3 a
3	Inbred line UFU-4413	0.45 b	80.0 b	3.9 b*#	5.7 b*	4.6 b*	0.61 a	3.7 a	1.9 b	1.8 b
4	Inbred line UFU-4411	0.53 b	80.0 b	4.1 b*#	5.7 b*	4.4 b*	0.55 a	4.1 a*	1.9 b	1.9 b
5	Inbred line UFU-2113	0.32 b	91.2 b*	4.6 a	6.2 a*	5.1 a*	0.61 a	3.7 a	2.3 b	2.2 a
6	Inbred line UFU-2521	0.73 a	100.0 a*	4.2 b*#	5.9 b*	4.3 b*	0.46 a*	3.1 b	2.2 b	2.4 a
7	Inbred line -2522	0.77 a	103.3 a*	4.6 a	6.6 a*	4.3 b*	0.57 a	3.2 b	3.1 a*	2.8 a#
8	Inbred line UFU-2523	1.31 a*	123.3 a*	4.2 b*#	6.5 a*	5.6 a*	0.53 a	3.1 b	2.6 a	2.3 a
9	Inbred line UFU-2513	0.89 a	90.0 b*	4.1 b*#	6.3 a*	5.3 a*	0.51 a*	3.6 a	2.5 a	2.3 a
10	F1 (UFU-2413 X UFU-4412)	1.07 a*	100.0 a*	4.3 b#	6.3 a*	6.1 a*	0.43 a*	3.1 b	1.8 b	1.6 b*
11	F1 (UFU-2413 XUFU-4413)	0.82 a	106.7 a*	4.8 a	6.7 a*	5.3 a*	0.51 a*	3.5 a	1.6 b	2.1 b
12	F1 (UFU-2413 X UFU-4411)	0.85 a	113.3 a*	4.4 a#	6.1 a*	5.6 a*	0.61 a	3.2 b	2.2 b	1.4 b*
13	F1 (UFU-2413 X UFU-2113)	0.71 a	110.0 a*	4.90 a	6.4 a*	4.7 b*	0.61 a	3.3 b	2.3 b	1.9 b
14	F1 (UFU-2413 X UFU-2521)	0.95 a	103.3 a*	4.70 a	6.3 a*	4.5 b*	0.56 a	3.4 b	1.5 b	2.7 a#
15	F1 (UFU-2413 X UFU-2522)	0.65 a	93.3 b*	4.50 a	6.1 a*	4.6 b*	0.61 a	3.4 b	2.3 b	1.9 b
16	F1 (UFU-2413 X UFU-2523)	0.89 a	106.7 a*	4.50 a	6.4 a*	5.3 a*	0.56 a	3.1 b	2.1 b	2.2 a
17	F1 (UFU-2413 X UFU-2513)	0.13 b	76.7 b#	3.50 b*#	5.4 b*	5.5 a*	0.41 a*#	3.8 a*	1.6 b	1.9 b
18	F1 (UFU-4412 XUFU-4413)	0.51 b	96.7 a*	4.50 a	6.6 a*	6.1 a*	0.56 a	3.7 a	1.9 b	2.2 a
19	F1 (UFU-4412 X UFU-4411)	0.53 b	100.0 a*	3.30 b*#	5.7 b*	4.6 b*	0.56 a	3.5 a	2.3 b	1.8 b
20	F1 (UFU-4412 X UFU-2113)	0.28 b	83.3 b*	3.90 b*#	5.6 b*	4.4 b*	0.45 a*	3.7 a	2.1 b	1.9 b
21	F1 (UFU-4412 X UFU-2521)	0.82 a	100.0 a*	3.9 b*#	5.8 b*	3.3 c#	0.51 a*	3.3 b	2.2 b	2.2 a
22	F1 (UFU-4412 X UFU-2522)	1.17 a*	96.7 a*	4.30 b*#	6.1 a*	4.3 b*	0.53 a	3.4 b	2.3 a	2.5 a
23	F1 (UFU-4412 X UFU-2523)	0.89 a	96.7 a*	4.10 b*#	5.9 b*	4.3 b*	0.56 a	3.5 a	3.3 a*#	2.4 a
24	F1 (UFU-4412 X UFU-2513)	0.87 a	93.3 b*	4.50 a	6.2 a*	4.1 b*	0.51 a*	3.6 a	2.1 b	1.8 b
25	F1 (UFU-4413 X UFU-4411)	0.81 a	93.3 b*	4.10 b*#	6.1 b*	4.6 b*	0.53 a	3.6 a	2.8 a	2.3 a
26	F1 (UFU-4413 X UFU-2113)	0.47 b	73.3 b#	3.90 b*#	5.6 b*	5.3 a*	0.43 a*	3.9a*	2.2 b	1.4 b*
27	F1 (UFU-4413 X UFU-2521)	0.81 a	90.0 b*	4.20 b*#	6.1 a*	5.1 a*	0.51 a*	3.2 b	2.5 a	2.3 a
28	F1 (UFU-4413 X UFU-2522)	0.83 a	123.3 a*	4.10 b*#	6.5 a*	4.9 a*	0.55 a	3.3 b	2.1 b	1.9 b
29	F1 (UFU-4413 X UFU-2523)	0.69 a	100.0 a*	4.30 b#	6.6 a*	4.6 b*	0.53 a	3.6 a	1.9 b	1.8 b
30	F1 (UFU-4413 X UFU-2513)	0.68 a	90.0 b*	4.20 b*#	6.2 a*	4.4 b*	0.53 a	3.7 a	2.3 b	1.9 b
31	F1 (UFU-4411 X UFU-2113)	0.25 b	90.0 b*	4.30 b*#	5.8 b*	4.6 b*	0.53 a	3.5 a	2.1 b	1.3 b*
32	F1 (UFU-4411 X UFU-2521)	0.54 b	86.7 b*	4.10 b*#	5.7 b*	4.2 b*	0.56 a	3.5 a	2.6 a	2.7 a#
33	F1 (UFU-4411 X UFU-2522)	0.66 a	100.0 a*	4.50 a	5.7 b*	4.1 b*	0.51 a*	3.1 b	2.6 a	2.6 a#
34	F1 (UFU-4411 X UFU-2523)	0.88 a	106.7 a*	4.20 b*#	6.1 a*	4.6 b*	0.46 a*	3.7 a	2.7 a	2.2 a
35	F1 (UFU-4411 X UFU-2513)	0.33 b	76.7 b#	4.10 b*#	5.9 b*	5.1 a*	0.51 a*	3.8 a*	1.4 b	1.3 b*
36	F1 (UFU-2113 X UFU-2521)	0.85 a	90.0 b*	4.60 a	6.3 a*	4.1 b*	0.53 a	3.1 b	2.5 a	2.2 a
37	F1 (UFU-2113 X UFU-2522)	0.74 a	106.7 a*	4.50 a	6.4 a*	4.6 b*	0.53 a	3.8 a	2.4 a	2.2 a
38	F1 (UFU-2113 X UFU-2523)	0.98 a	110.0 a*	4.50 a	6.4 a*	5.1 a*	0.54 a	3.2 b	2.5 a	1.9 b
39	F1 (UFU-2113 X UFU-2513)	0.96 a	103.3 a*	4.70 a	6.3 a*	4.6 b*	0.57 a	3.4 b	2.2 b	2.1 a
40	F1 (UFU-2521 X UFU-2522)	0.78 a	106.7 a*	4.50 a	6.3 a*	4.3 b*	0.47 a	3.2 b	1.8 b	1.8 b
41	F1 (UFU-2521 X UFU-2523)	1.02 a	100.0 a*	4.10 b*#	5.8 b*	4.1 b*	0.53 a	3.2 b	2.2 b	2.2 a
42	F1 (UFU-2521 X UFU-2513)	1.31 a*	116.7 a*	4.20 b*#	6.4 a*	4.3 b*	0.57 a	3.9 a*	2.1 b	1.6 b*
43	F1 (UFU-2522 X UFU-2523)	1.14 a*	110.0 a*	4.30 b#	6.4 a*	4.6 b*	0.53 a	3.8 a	1.9 b	2.1 b
44	F1 (UFU-2522 X UFU-2513)	1.12 a*	110.0 a*	4.70 a	6.5 a*	4.1 b*	0.51 a*	3.1 b	2.7 a	2.5 a
45	F1 (UFU-2523 X UFU-2513)	1.01 a	106.7 a*	4.40 a#	6.5 a*	5.1 a*	0.53 a	3.3 b	2.2 b	1.9 b
46	cv. Vitalino 32 (Check)	0.36 b	56.7 b	4.90 a	4.3 c	2.3 c	0.71 a	3.1 b	1.9 b	2.6 a
47	UFU-57 Recurrent genitor	0.79 a	110.0 a	5.10 a	6.1 a	5.3 a	0.61 a	3.4 b	2.2 b	1.7 b
	Means	0.74	0.09	4.34	6.11	4.69	0.53	3.44	2.21	2.05
	CV (%)	39.1	13.7	6.2	6.6	13.3	14.7	9.1	19.3	18.5
	Contrasts (y)	Estimate								
C1=	hybrids UFU *vs.* inbred lines UFU	0.15*	5.61**	0.06^{ns}	0.16^{ns}	-0.24*	-0.01^{ns}	0.01^{ns}	-0.01^{ns}	-0.10^{ns}
C2=	hybrids UFU *vs.* cv. Vitalino 32	0.42*	42.38**	-0.61*	1.84*	2.31*	-0.18 ^{ns}	0.36*	0.30*	-0.58*
C3=	inbred lines UFU *vs.* UFU-57	4.89*	731.20**	33.00*	47.80**	38.30**	4.20*	27.60*	17.70**	17.40*
C4=	cv. Vitalino 32 *vs.* UFU-57	-0.43*	-53.30**	-0.20*	-1.80*	-3.00*	0.10 ^{ns}	-0.30*	-0.30*	0.90*

PP: Production per plant; MFW: Mean fruit weight; TD: Transversal diameter of the fruit; LD: Longitudinal diameter of the fruit; PT: pulp thickness; NL: Number of lobules per fruit, SS: Soluble solids content; LC: Lycopene content; BC: β-carotene content. [1]Means followed by distinct letters in the column belong to the same group by the Scott-Knott test at the 0.05 significance level. * Means in the column differ from recurrent genitor UFU-57 by Dunnett's test at the 0.05 significance level. [#]Means in the column differ from cv. Vitalino 32 by Dunnett's test at the 0.05 significance level. (y) **, *, ns = significant $p < 0.01$, $p < 0.05$ and non-significant, respectively, by the Scheffé test. *Vs. = Versus* .

Inbred line 8 and experimental hybrids 41, 42, 43, 44, and 45 stood out for the variables PP and MFW, which are good indicators that directly related to production yield, which is an important parameter used to select superior genotypes in breeding programs (Finzi *et al.*, 2017). Thus, the genotypes presented here are promising for such characteristics.

Using the Dunnett's test, the following genotypes were compared with UFU-57 and had lower TD: 1, 2, 3, 4, 6, 8, 9, 10, 12, 17, 19, 20, 21, 22, 23, 25, 26, 27, 28, 29, 30, 31, 32, 34, 35, 41, 42, 43, and 45. These same genotypes, except 10, 12, 29, 43, and 45, also showed lower TD compared to the hybrid Vitalino 32 (Table 1). About LD, Dunnett's test showed fruits of similar length to those produced by UFU-57 and superior to Vitalino 32 (Table 1).

Regarding LD and TD characteristics, the genotypes that showed the greatest prominence were 5, 7, 13, 14, 36, and 44. These characteristics are extremely important for determining the shape of tomato fruits, a decisive factor in their commercialization. The market preference is for oblong and round fruits. The ratio of transverse diameter to longitudinal diameter (TD/LD) is <1 for flat shaped fruits; = 1 for round fruits; and >1 for oblong shaped fruits (Andrade *et al.*, 2014). Most of the genotypes characterized in this study presented TD/LD ratio <1, therefore corresponding to flat shapened fruits.

All genotypes presented fruits with NL similar to UFU-57 and superior to Vitalino 32 (Dunnett's, 0.05 significance) (Table 1). About PT, genotype 17 was inferior compared to UFU-57. Inbred lines 6 and 9 and hybrids 10, 11, 17, 20, 21, 24, 26, 27, 33, 34, 35, and 44 showed PT inferior to that of the fruits produced by Vitalino 32 (Table 1).

Tomato fruit firmness is one of the indispensable factors for improved postharvest quality, also becoming an important parameter in genetic improvement (Duarte *et al*., 2023). According to this author, tomato fruits with lower NL and higher PT are firmer. The genotypes 4, 7, 15, 16, 19, 23, 28, 32, 39, and 42 stood out as those with firmer fruits due to lower NL and higher PT. Values between 1.9 and 4.6 for NL were observed in the evaluation of tomato hybrids for agronomic potential (Assunção *et al.*, 2018), results that agree with those found in the present study (Table 1).

Dunnett's test showed superiority in SS for inbred line 4 and hybrids 17, 26, 35, and 42 in relation to Vitalino 32. The other genotypes showed similarity in SS with UFU-57 (Table 1).

Genotypes 3, 4, 5, 9, 11, 17, 18, 23, 24, 25, 26, 29, 30, 31, 32, 34, 35, 37, 42, and 43 highlighted for the SS characteristic, that is directly related to the fruit's sweetness and an important trait for consumer's preference (Gomes *et al*., 2021). In view of this statement, the genotypes mentioned above stand out in the consumer market.

As shown in Dunnett's test, genotype 23 was superior in LC compared to UFU-57 and Vitalino 32. Inbred line 7 also showed higher LC compared to Vitalino 32 (Table 1). This test showed that, for BC, inbred line 7 and hybrids 14, 32, and 33 where superior than UFU-57. Furthermore, inbred line 1 and hybrids 10, 12, 26, 31, 35, and 42 showed lower BC contents than Vitalino 32.

Regarding the LC and BC characteristics, genotypes 7, 8, 32, 33, and 44 stood out. Higher LC and BC are extremely important because they promote significant increases in fruit color and nutritional quality. In addition, fruits rich in these bioactive compounds have more antioxidant properties, preventing diseases such as cancer and aiding human health (Nellis *et al.*, 2017). In this sense, the genotypes that stood out for these characteristics are promising for a tomato breeding program.

The superiority of hybrids against inbred lines was confirmed by the significance of the contrasts of interest (Scheffé test), especially regarding PP and MFW (Table 1). This result is important for showing that the experiment indicates the dissimilarity between treatments, enabling the validation of different vegetation indexes. However, genetic dissimilarity is mostly evaluated using dendrograms (Clemente *et al.*, 2021).

The UPGMA dendrogram generated using the dissimilarity matrix obtained by the generalized Mahalanobis distance showed a CCC of 0.90, indicating that the grouping pattern of the genotypes is reliable and represents the genetic dissimilarity matrix (Mantel, 1967). The cut-off line was drawn in the dendrogram at the point where an abrupt level change occurred (Cruz *et al.*, 2011). The cut was made at 13% dissimilarity, allowing the separation of genotypes into 11 distinct groups (Figure 2).

Among the eleven groups formed, five comprised hybrids: three groups with only one genotype each (13, 14, and 21) and two groups of three genotypes each (10, 11, and 18; and 17, 26, and 35). These data mainly suggest the superiority of these hybrids to the inbred lines, demonstrating a positive selection gain over generations. These genotypes may be used in future breeding programs since they presented high genetic variability and stood out for most of the agronomic performance variables by the mean test (Table 1).

The commercial hybrid (Vitalino 32) was isolated in one group. The recurrent genitor UFU-57 was grouped with hybrid 12, suggesting a great potential for PP and fruit quality for hybrid 12, as the recurrent genitor presented such characteristics.

Based on the criteria proposed, the most important characteristics for the dissimilarity of the genotypes were TD, BC, LD, and NL (Singh, 1981). The transverse diameter is important in fruit quality classification. Fruits with higher values of TD are larger and more attractive to the consumer market.

This result is positive for tomato breeding programs because it may contribute to obtain fruits with high values of TD and, consequently, higher commercial quality (Andrade *et al.*, 2014).

The hybrids, compared to the inbred lines, showed increased vegetative development throughout their cycle, according to the values of vegetative index found (Figure 3). However, some genotypes did not present the same performance, which can be associated with plant's senescence, especially for having a determinate growth habit. In fact, the phenomenon of heterosis is evident when comparing hybrids and inbred lines. Hybrid plants are more vigorous and productive (Hochholdinger & Baldauf, 2018).

Inbred line 4 showed balance in the response of the Chlorophyll Vegetation Index (CVI), Green Normalized Difference Vegetation Index (GNDVI), and Soil Adjusted Vegetation Index (SAVI) from 30 to 45 days after transplanting (DAT). Subsequently, we observed a decrement in SAVI, an increment in GNDVI, and CVI. On the other hand, inbred line 5 had a decrement in vegetative development according to the SAVI index and stability for CVI and GNDVI from 30 to 45 DAT. After 45 DAT, the values of SAVI, CVI, and GNDVI increased by 70, 15, and 14%, respectively.

The spectral behavior of the targets and the working scale of the vegetative index are subject to variations caused by the architecture of the canopy and the sensor view geometry, besides other factors, which can vary according to the crop in question (Wang *et al.*, 2017). This may explain the decrease and stability in index values calculated for inbred lines 4 and 5, which presented low canopy development, interfering negatively in the results.

Hybrids 14, 16, 18, and 19 showed an increment of 40, 50, and 20% for the GNDVI, CVI, and SAVI indexes, respectively. These genotypes had similar behavior to UFU-57 (Figure 3), indicating a healthier plant with better vegetative growth and, consequently, higher productivity (Ramoelo *et al.*, 2012).

The hybrid Vitalino 32 maintained a balance in vegetative development from 30 to 45 DAT according to the GNDVI and CVI indexes. In contrast, for SAVI, it had slight increase for the same characteristic. Subsequently, the three indexes decreased, which can be attributed to the model on which they are based, that is the opposite behavior of the reflectance of vegetation in the visible region, i.e., the higher the density of vegetation, the lower the reflectance, and the lower the plant density, the higher the reflectance (Maciel *et al.*, 2019). In other words, as vegetative development increased over time, reflectance decreased.

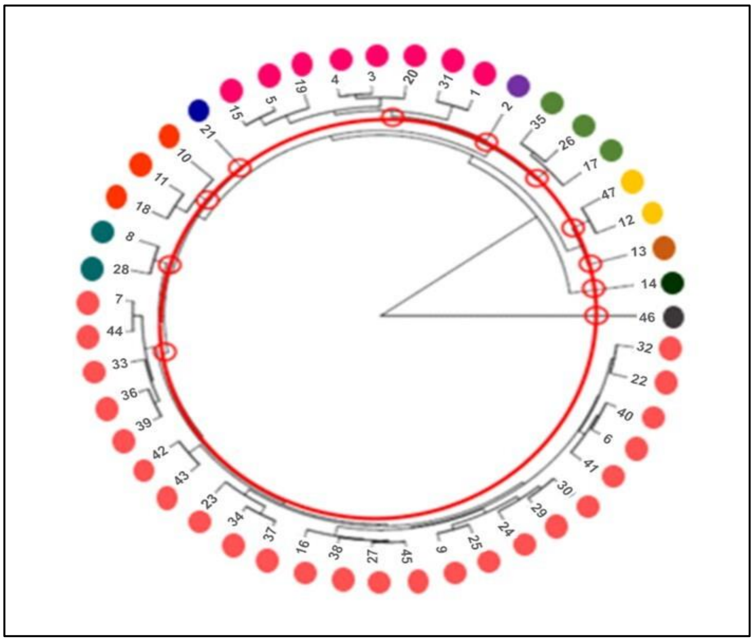

Figure 2. Circular dendrogram of the genetic dissimilarity among 47 genotypes, obtained by the simple agglomerative hierarchical clustering method UPGMA, based on the generalized Mahalanobis distance (D²). Colored circles represent the groups defined by the cut-off method. Monte Carmelo, UFU, 2020.

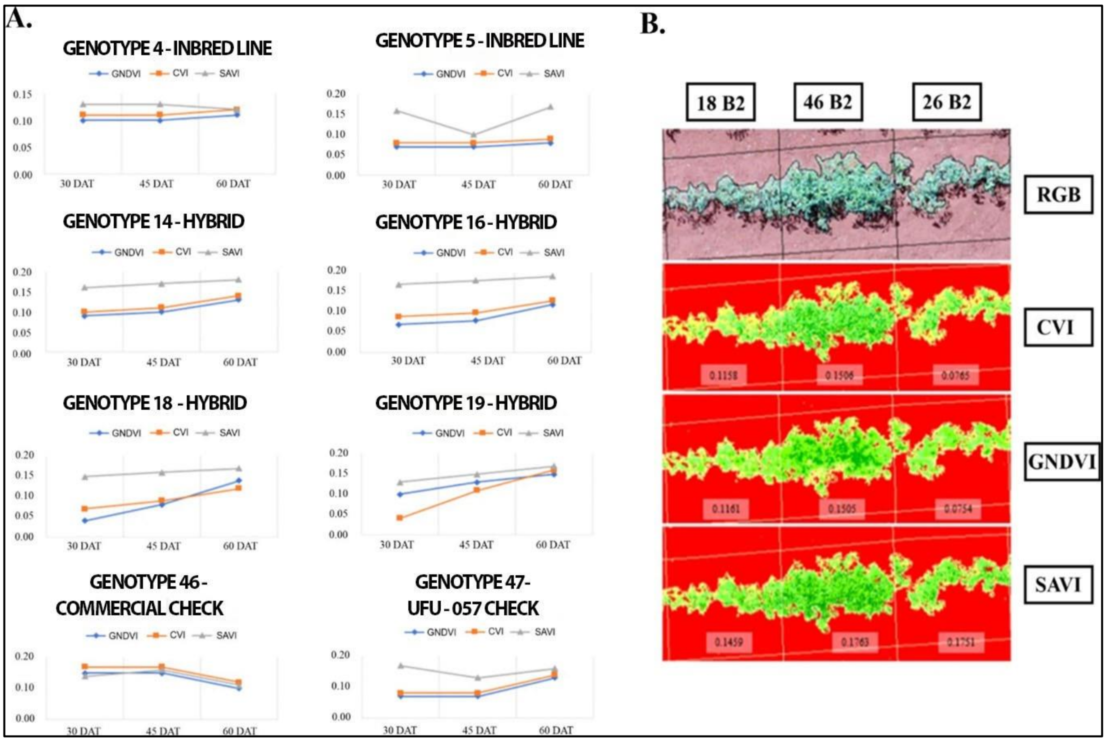

Figure 3. Graphical representations of the vegetative growth of two inbred lines (genotypes 4 and 5), four hybrids (genotypes 14, 16, 18, and 19), and the two checks (genotypes 46 and 47) (A). B. Tomato genotypes 18, 46, and 26 determined in block 2. From top to bottom, RGB photo and measurement of the indices (B). RGB: red, green, and blue. CVI: Chlorophyll Vegetation Index; GNDVI: Green Normalized Difference Vegetation Index; SAVI: Soil Adjusted Vegetation Index. Monte Carmelo, UFU, 2020.

The vegetative development of the inbred lines and hybrids are well represented by the vegetation index in Figure 3. Using this method in future analyses can be of great impact since the current methods of measuring vegetative development, such as leaf area index (LAI), involve destructive sampling that is not practical in breeding programs. Therefore, technologies that utilize drones and proximal sensors open new opportunities for performing several evaluations during the cycle without damaging the plant (Potgieter *et al.*, 2017; Clemente *et al.*, 2021).

The two check treatments did not have a good representation of their vegetative development. Low values were observed for the three indexes in the third flight (45 to 60 DAT) for the hybrid Vitalino 32. The same occurred with the SAVI index in the second flight (30 to 45 DAT) for UFU-57.

The CVI index stood out for this analysis of vegetative development because it was the only index that showed an increase in the materials over time in all cases, even if minimal. In fact, CVI had already stood out among the three indexes in the relative contribution of characters. The others, as already mentioned, showed small decreases at certain times. This result reveals that CVI has greater potential for being used in further studies as a more efficient parameter when analyzing vegetative development.

Vegetation index can also serve as parameter for selecting more productive materials and fruit quality. Additionally, productivity can be indirectly evaluated by vegetative development (Rosas *et al.*, 2019).

Analyzing the images classified by the CVI, GNDVI, and SAVI indexes, we could observe a consistency between the results obtained. When compared to the RGB orthoimage, i.e., the measurement of the indexes demonstrates mathematically where the vegetation is developed. The representative genotypes 18, 46, and 26 of block 2 were sampled to demonstrate such effects (Figure 3).

The RGB image shows the vegetation differences of the three plots of the study, highlighting that plot 46 showed greater vegetative development than plots 18 and 26. Such effects are evident when analyzing the CVI, GNDVI, and SAVI indexes in graphs (Figure 3).

This result confirms that vegetation index, calculated by image, can be used in evaluations of determined tomato hybrids since the values obtained were consistent with what was observed in the field. Moreover, this study showed that vegetation index could distinguish hybrids (heterosis) from lines (inbreeding) to a greater extent, as recommended by Silva *et al.* (2022).

The CVI index showed the greatest consistency regarding the agronomic characteristics evaluated. Even for smaller magnitudes (inbred lines *versus* inbred lines and hybrids *versus* hybrids) the CVI index could differentiate genotypes. However, other vegetation index should be evaluated in further research.

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