Research Article

Assessment of leaf anatomic and physiological characteristics and genetic divergence among *Coffea arabica* L. cultivars in the Brazilian Savanna[1]

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ABSTRACT

The knowledge on cultivars is essential for parental choosing on breeding programs. This research aimed to study the genetic divergence of *Coffea arabica* L. cultivars from a germoplasm bank of the Embrapa Cerrados, Brazil, for leaf anatomic and physiological characteristics. A total of 23 cultivars were evaluated: Acaiá Cerrado MG1474, Araponga MG1, Catiguá MG1, Catiguá MG2, Catiguá MG3, Catiguá MG3 P4, Catiguá MG3 P5, Catiguá MG3 P7, Catiguá MG3 P9, Catiguá MG3 P23, Catiguá MG3 P51, Catuaí Amarelo IAC 62, Catuaí Vermelho IAC 15, Catuaí Vermelho IAC 81, Catuaí Vermelho IAC 99, Caturra Vermelho MG0187, Guatenano Colis MG0207, Mundo Novo IAC 379-19, Paraíso MG1, Pau Brasil MG1, Sacramento MG1, San Ramon MG0198 and Topázio MG1190. In addition to the genetic divergence, the broad sense heritability and coefficient of genetic and environmental variation were also evaluated. All characteristics showed high coefficients of genetic variation and heritability values greater than 70 %, indicating a predominance of genetic over environmental factors, and that these are characteristics likely to obtain genetic gain. Catiguá MG1, Catiguá MG3 P51 and Topázio MG1190 stood out, with superior gas exchange characteristics. Attributes related to gas exchange were important for cultivar differentiation, demonstrating that they can be used in the early selection of *Coffea arabica* L. genotypes.

KEYWORDS: Genetic breeding, coffee tree, gas exchange.

RESUMO

Avaliação de características anatômicas e fisiológicas foliares e divergência genética entre cultivares de *Coffea arabica* L. no Cerrado

O conhecimento das cultivares é essencial para a escolha dos pais em programas de melhoramento. Objetivou-se estudar a divergência genética de cultivares de *Coffea arabica* L. de um banco de germoplasma da Embrapa Cerrados, quanto às características anatômicas foliares e fisiológicas. Foram avaliadas 23 cultivares: Acaiá Cerrado MG1474, Araponga MG1, Catiguá MG1, Catiguá MG2, Catiguá MG3, Catiguá MG3 P4, Catiguá MG3 P5, Catiguá MG3 P7, Catiguá MG3 P9, Catiguá MG3 P23, Catiguá MG3 P51, Catuaí Amarelo IAC 62, Catuaí Vermelho IAC 15, Catuaí Vermelho IAC 81, Catuaí Vermelho IAC 99, Caturra Vermelho MG0187, Guatenano Colis MG0207, Mundo Novo IAC 379-19, Paraíso MG1, Pau Brasil MG1, Sacramento MG1, San Ramon MG0198 e Topázio MG1190. Além da divergência genética, foram avaliados a herdabilidade de sentido amplo, coeficiente de variação genética e ambiental. Todas as características apresentaram altos coeficientes de variação genética e valores de herdabilidade superiores a 70 %, indicando predominância de fatores genéticos sobre ambientais, e que essas são características passíveis de se obter ganho genético. Catiguá MG1, Catiguá MG3 P51 e Topázio MG1190 se destacaram com características de trocas gasosas superiores. Atributos relacionados às trocas gasosas foram importantes para a discriminação das cultivares, o que demonstra que podem ser utilizados na seleção precoce de genótipos de *Coffea arabica* L.

PALAVRAS-CHAVE: Melhoramento genético, cafeeiro, trocas gasosas.

INTRODUCTION

The coffee crop has great social and economic importance in Brazil (Volsi et al. 2019), and its yield may be attributed to genetic breeding programs which allowed the obtention of more productive cultivars with characteristics of agronomic interest (Coltri et al. 2019, Purba et al. 2019).

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In Brazil, about 20 % of *Coffea* species are preserved in germplasm banks, besides inter- and intraspecific hybrids used as source of genetic variability (Eira et al. 2007). Research has characterized these collections and identified promising materials (Ferrão et al. 2008, Guedes et al. 2013, Giles et al. 2019). In these collections, in addition to exotic accessions, there are also cultivars in current use that may be included in breeding programs with success on the enhancement of important characteristics. However, some desirable characteristics require a longer evaluation time and are still little studied. Leaf anatomy studies associated to those of coffee physiology may be an accurate alternative to assist with materials of higher agronomic interest (Queiroz-Voltan et al. 2014, Viana et al. 2018, Giles et al. 2019).

The optimum mean annual temperatures for *C. arabica* range from 18 to 23 ºC under cultivation conditions (DaMatta et al. 2018). The knowledge regarding cultivar potential on cultivation environments such as Cerrado (Brazilian Savanna), where the average annual temperature is 24 ºC, with a maximum of 34.2 ºC (Nascimento & Novais 2020), is of extreme importance. Thus, the identification of genotypes better adapted to the climatic conditions of this biome may contribute to accelerate breeding programs. Therefore, this research aimed to characterize *Coffea arabica* L. cultivars, estimate genetic divergence regarding physiological and anatomical characteristics, and identify the most divergent ones for future hybridizations in coffee breeding programs.

MATERIAL AND METHODS

The experiments were conducted in June 2016, in Planaltina, Federal District, Brazil, where the climate is Aw, according to Köppen, the average annual rainfall is 1,600 mm, with two typical rainy and dry seasons, the average annual temperature is 22 ºC and the altitude is 1,000 m (Alvares et al. 2013). The soil of the area is classified as Dark Red Latosol with clay texture (Santos 2013).

A total of 16 *Coffea arabica* L. cultivars from the Embrapa Cerrados Germplasm Bank were evaluated (Acaiá Cerrado MG1474, Araponga MG1, Catiguá MG1, Catiguá MG2, Catuaí Amarelo IAC 62, Catuaí Vermelho IAC 15, Catuaí Vermelho IAC 81, Catuaí Vermelho IAC 99, Caturra Vermelho MG0187, Guatenano Colis MG0207, Mundo Novo IAC 379-19, Paraíso MG1, Pau Brasil MG1, Sacramento MG1, San Ramon MG0198 and Topázio MG1190), as well as 7 strains from the Catigua MG3 cultivar: Catigua MG3 with no marking (NM), Catiguá MG3 P4, Catigua MG3 P5, Catigua MG3 P7, Catigua MG3 P9, Catigua MG3 P23 and Catigua MG3 P51, to which the letter P corresponds to progenies of individual plants selected in experiments conducted in Turmalina, Minas Gerais, Brazil. These were selected in order to represent productive materials used in the different producing regions of Brazil.

The experimental design was completely randomized, with six plants per replicate. Six-year-old coffee plants were planted at a spacing of 3.8 x 0.7 m, and the management practices were carried out according to technical recommendations for coffee in the region. Irrigation was performed by a central pivot system with watering shift every five days. For data collection, completely expanded leaves, from the third or fourth pair at the middle third of each genotype plagiotropic branch, were selected.

The collected leaves were conditioned according to Johansen (1940). The plant material was dehydrated in an alcoholic series, included in methacrylate and sectioned at about 8-mm thickness, using a rotative microtome, observing the leaf transversal sections. The obtained sections were colored with toluidine blue (O'Brien et al. 1964) and the slides built using Entellan resin (Merck®). Paradermal sections were obtained through epidermis impression, using the universal instant adhesive method cyanoacrylate ester (Super Bonder® Locite-Henkel, São Paulo, Brazil) (Segatto et al. 2004).

The slides were photographed using an optical microscope (BX 60, Olympus Optical Co Ltd, Tokyo, Japan) with a digital camera (Canon A630 - Canon Inc., Tokyo, Japan). For each replicate, nine slides containing the transversal sections (three images from the main rib, leaf limb and cuticle from the adaxial surface) and three slides from three different paradermal sections were evaluated. The images were analyzed by the UTHSCSA-Imagetool software, version 3.0 (UTHSCSA 2017).

The analyzed characteristics on transversal sections were: adaxial cuticle thickness (μm), adaxial epidermis thickness (μm), palisade parenchyma thickness (μm), spongy parenchyma thickness (μm), abaxial epidermis thickness (μm), number of xylem vases, xylem diameter (μm) and phloem thickness between procambium and sclerenchyma (μm). For paradermal sections, the number of stomata mm^{-2} (stomatal density) and ratio between stomatal polar and equatorial diameter were analyzed.

The gas exchange was evaluated using a portable system for gas analysis through infrared (IRGA LI-6400XT Portable Photosynthesis System - Licor Biosciences, Lincoln, USA). The stomatal conductance (gs - mol H_2O m^{-1} s^{-1}), transpiratory rate (E - mmol H_2O m^{-2} s^{-1}), net photosynthetic rate (A - μmol CO_2 m^{-2} s^{-1}), water-use efficiency (WUE - μmol CO_2/mol H_2O) (A/E) (Zhang et al. 2001), intracellular CO_2 concentration on the mesophyll under external concentration (CiCa ratio - μmol CO_2) and carboxylation efficiency (CUE - μmol CO_2 m^{-2} s^{-1}/μmol CO_2 mol^{-1}) (A/Ci) were also analyzed. The evaluations were carried out between 8 and 11 a.m., under artificial light (1,000 μmol m^{-2} s^{-1}).

The relative content of chlorophyll a, b and total were obtained using a portable chlorophyll meter ClorofiLOG (Falker Automação Agrícola, Brasil), which supplies values named Falker chlorophyll index, proportional to the chlorophyl absorbance (Barbieri Júnior et al. 2012).

The data were evaluated for normality by the Shapiro-Wilk's test and homoscedasticity by the Bartlett test (Snedecor & Cochran 1989). Analysis of variance (Anova) was performed for each analyzed characteristic and the averages for the cultivars were compared by the Scott-Knott test at 5 % of probability. The broad-sense heritability (h^2), coefficient of genetic variation (CVg), coefficient of environmental variation (CVe) and ratio between these two coefficients (CVg/CVe) were also evaluated.

For genetic divergency, a genetic distance matrix, based on the generalized Mahalanobis distance, was used. The grouping was carried out by the unweighted pair group method using arithmetic averages (UPGMA) hierarchical method from the Genes software (Cruz 2013) and the canonical variables grouping with the Candisc package from the R software (Friendly & Fox 2017, R Core Team 2019).

RESULTS AND DISCUSSION

Heritability oscillated from 4.55 to 13.11 % for the leaf anatomic characteristics and the highest values were observed for number of xylem vases and spongy parenchyma thickness (Table 1). For the physiological characteristics, this coefficient oscillated from 2.99 to 57.58 % and the highest values were observed for stomatal conductance (Table 1).

The environmental coefficient of variation (CVe) oscillated from 2.7 % for the ratio between polar and equatorial stomatal diameter to 9.88 % for number of xylem vases. Except for the palisade parenchyma thickness, the evaluated anatomic and physiological characteristics had a coefficient ratio (CVg/CVe) over 1 (Table 1), which indicates a predominance of genetic factors over environmental ones (Ferrão et al. 2008). These results evidence that the characteristics evaluated in this study are likely to achieve genetic progress. According to Vencovsky (1987), there is a very favorable situation for obtaining gains in selection when the CVg/CVe ratio

Table 1. Estimated coefficient of genetic (CVg) and environmental (CVe) variation, and ratio between these coefficients (CVg/CVe) and broad-sense heritability (h^2) for leaf anatomic and physiological characteristics in *Coffea arabica* L. genotypes from the Embrapa Cerrados Germplasm Bank.

Anatomic characteristics[(1)]	CVg	CVe	CVg/CVe	h²
CUT	6.21	5.22	1.19	89.46
ABE	8.58	5.62	1.53	93.34
ADE	10.38	6.43	1.61	93.98
PP	4.55	7.69	0.59	67.74
SP	12.11	9.47	1.28	90.76
PT	8.93	6.35	1.41	92.22
XVD	8.47	4.91	1.72	94.69
NXV	13.11	9.88	1.33	91.36
SPDED	5.92	2.70	2.19	96.65
SD	9.43	7.58	1.24	90.26
Physiological characteristics[(2)]				
A	27.34	9.42	2.90	98.06
gs	57.58	14.25	4.04	98.99
E	20.86	14.71	1.42	92.35
CiCa	21.18	9.03	2.34	97.06
WUE	24.20	15.68	1.54	93.46
CUE	47.23	22.65	2.09	96.31
Cla	2.99	1.51	1.99	95.98
Clb	15.02	3.82	3.94	98.94
ClT	6.87	1.82	3.77	98.84

[(1)] CUT: adaxial cuticle thickness; ABE: abaxial epidermis thickness; ADE: adaxial epidermis thickness; PP: palisade parenchyma thickness; SP: spongy parenchyma thickness; PT: phloem thickness between procambium and sclerenchyma; XVD: xylem diameter; NXV: number of xylem vases; SPDED: ratio between stomatal polar and equatorial diameters; SD: stomatal density. [(2)] A: net photosynthetic rate; gs: stomatal conductance; E: transpiration rate; CiCa: intracellular CO_2 concentration on the mesophyll under external concentration; WUE: water-use efficiency; CUE: carboxylation efficiency; Cla: Falker chlorophyll a index; Clb: Falker chlorophyll b index; ClT: Falker total chlorophyll index.

tends to or is greater than 1, since, in these cases, the genetic variation exceeds the environmental variation.

The heritability coefficient represents the reliability with which the phenotypic value represents the genotypic value; thus, characteristics with heritability greater than 70 % may be considered to have a high value (Ivoglo et al. 2008). It was observed that most the heritability values (h^2) are superior to 70 % for both the anatomic and physiological characteristics (Table 1). These results confirm the predominance of additive gene effects on all characteristics. Therefore, the direct selection would be effective for genetic breeding. The results of the present study are corroborated by Giles et al. (2019), who verified a predominance of genetic components, in relation to environmental factors, on anatomic aspects of coffee leaves. On the other hand, the palisade parenchyma thickness was the only characteristic which had inferior values for heritability (Table 1), indicating a higher environmental influence for this characteristic, as observed in other studies that recorded changes in this characteristic due to environmental stimuli (Assis et al. 2019, Pérez-Molina et al. 2021). This is possibly a more plastic tissue, and its variations can provide optimization in the photosynthetic activity.

The Catiguá MG2 and Mundo Novo IAC 379-19 cultivars showed a greater cuticle thickness on the adaxial surface (Table 2), which can increase the radiation reflection and isolate the internal tissues (Kumar & Tieszen 1980, Silva et al. 2004), in addition to favoring the reduction in the transpiration rate, as observed for the genotypes in this study (Table 3). This characteristic can be extremely important in dry environments, since, although the cuticular transpiration is considered low, it represents 5 to 10 % of the transpiration rate (Ferri & Lamberti 1960). The result observed for Mundo Novo IAC 379-19 corroborates that of Batista et al. (2010), who found a thicker cuticle in this material, indicating that this may be a characteristic of this cultivar.

Another plant strategy to avoid excessive transpiration is to invest in a greater thickness of leaf blade tissues, in addition to changes in stomatal

Table 2. Mean values for leaf anatomical characteristics[1] (µm) evaluated in *Coffea arabica* L. cultivars belonging to the Embrapa Cerrados Active Germplasm Bank.

Identification[2]	Cultivar	CUT	ADE	PP	SP	ABE	PT	XVD	NVX	SPDED	SD
AC	Acaiá Cerrado MG 1474	4.44 b*	28.86 a	66.22 a	178.73 b	17.07 a	54.01 b	14.63 b	131.83 b	1.95 b	187.24 b
A	Araponga MG1	4.34 c	25.52 b	71.97 a	213.91 a	14.82 b	71.23 a	15.69 b	150.72 a	1.87 c	203.54 a
MG1	Catiguá MG1	4.65 b	30.60 a	64.22 a	159.38 b	19.72 a	63.98 a	17.85 a	113.39 c	1.85 c	200.28 a
MG2	Catiguá MG2	4.98 a	30.62 a	62.58 a	148.81 b	17.84 a	61.21 a	17.69 a	132.83 b	1.94 b	183.32 b
P4	Catiguá MG3 P4	4.60 b	29.96 a	66.40 a	185.08 a	19.31 a	62.81 a	16.18 b	135.06 b	1.80 c	183.97 b
P5	Catiguá MG3 P5	4.30 c	29.71 a	63.79 a	193.92 a	18.11 a	60.26 a	17.54 a	132.61 b	1.83 c	182.67 b
P7	Catiguá MG3 P7	4.51 b	29.09 a	55.19 a	183.24 a	18.49 a	59.98 a	18.49 a	126.94 b	1.83 c	178.10 b
P9	Catiguá MG3 P9	4.20 c	31.21 a	54.65 a	177.27 a	19.93 a	59.41 a	18.08 a	98.39 c	2.00 b	189.84 b
P23	Catiguá MG3 P23	4.25 c	28.09 a	63.45 a	179.98 b	17.45 a	60.06 a	17.53 a	134.11 b	1.85 c	209.42 a
P51	Catiguá MG3 P51	4.18 c	30.74 a	60.41 a	165.65 b	17.61 a	51.09 b	15.06 b	109.56 c	1.90 b	197.67 a
NM	Catiguá MG3 NM	4.23 c	26.91 b	62.09 a	172.54 b	18.13 a	64.39 a	16.74 a	156.89 a	1.99 b	187.24 b
C62	Catuaí Amarelo IAC 62	4.19 c	28.99 a	58.12 a	219.39 a	17.84 a	65.53 a	17.87 a	136.17 b	1.90 b	187.24 b
C15	Catuaí Vermelho IAC 15	4.53 b	29.67 a	67.53 a	202.77 a	17.88 a	71.84 a	16.02 b	171.00 a	1.89 c	202.24 a
C81	Catuaí Vermelho IAC 81	4.39 c	25.40 b	61.79 a	161.08 b	14.60 b	67.03 a	16.15 b	154.06 a	1.98 b	214.64 a
C99	Catuaí Vermelho IAC 99	4.44 b	27.97 a	59.04 a	190.23 a	16.75 a	64.38 a	15.57 b	153.39 a	1.91 b	197.02 a
C	Caturra Vermelho MG 0187	4.32 c	25.58 b	63.70 a	160.10 b	15.30 b	64.27 a	15.33 b	128.89 b	1.86 c	208.76 a
G	Guatenano Colis MG0207	4.35 c	27.67 a	53.70 a	205.02 a	17.46 a	65.04 a	15.89 b	133.17 b	1.93 b	204.85 a
MN	Mundo Novo IAC 379-19	4.80 a	23.34 b	57.71 a	162.24 b	15.69 b	52.86 b	15.63 b	108.67 c	1.99 b	180.06 b
P	Paraíso MG1	4.25 c	33.00 a	60.42 a	173.28 b	18.12 a	61.05 a	19.11 a	113.67 c	2.29 a	147.44 b
PB	Pau Brasil MG1	4.02 c	28.41 a	63.71 a	194.70 a	18.52 a	64.65 a	17.01 a	124.06 c	1.78 c	219.85 a
S	Sacramento MG1	3.69 c	28.62 a	63.44 a	185.63 a	18.16 a	62.10 a	17.24 a	116.06 c	1.94 b	157.23 b
SR	San Ramon MG 0198	4.37 c	25.46 b	63.38 a	137.40 b	14.20 b	51.90 b	13.89 b	101.50 c	1.84 c	167.01 b
T	Topázio MG 1190	4.17 c	26.44 b	63.45 a	156.67 b	16.67 a	53.84 b	14.48 b	135.28 b	1.77 c	196.37 a

* Means followed by the same letter in the column belong to the same group, according to the Scott-Knott test, at 5 % of probability. [1] CUT: adaxial cuticle thickness; ABE: abaxial epidermis thickness; ADE: adaxial epidermis thickness; PP: palisade parenchyma thickness; SP: spongy parenchyma thickness; PT: phloem thickness between procambium and sclerenchyma; XVD: xylem diameter; NXV: number of xylem vases; SPDED: ratio between stomatal polar and equatorial diameters; SD: stomatal density. [2] Representative identification of each cultivar.

Table 3. Mean values of the evaluated physiological characteristics[1] in *Coffea arabica* L. cultivars belonging to the Embrapa Cerrados Active Germplasm Bank.

Identification[2]	Cultivar	A	gs	E	CiCa	WUE	CUE	Cla	Clb	ClT
AC	Acaiá Cerrado MG 1474	5.60 d*	0.06 d	1.19 c	0.54 b	4.91 b	0.03 b	464.67 b	267.83 c	732.50 c
A	Araponga MG1	7.43 c	0.07 c	1.73 c	0.47 b	4.47 c	0.06 a	439.83 c	229.17 e	669.00 e
MG1	Catiguá MG1	10.58 a	0.16 b	1.48 c	0.71 a	7.23 a	0.04 b	458.00 b	252.33 d	710.33 d
MG2	Catiguá MG2	8.01 c	0.08 c	1.44 c	0.52 b	5.75 b	0.04 b	452.50 c	271.50 c	724.00 c
P4	Catiguá MG3 P4	7.28 c	0.06 d	1.55 c	0.40 c	4.69 c	0.07 a	448.00 c	250.83 d	698.83 d
P5	Catiguá MG3 P5	11.13 a	0.16 b	1.97 b	0.68 a	5.75 b	0.04 b	465.83 b	244.50 d	710.33 d
P7	Catiguá MG3 P7	8.40 b	0.10 c	1.61 c	0.59 a	5.57 b	0.04 b	473.67 a	264.50 c	738.17 c
P9	Catiguá MG3 P9	6.45 c	0.05 d	1.46 c	0.39 c	4.46 c	0.06 a	484.33 a	307.83 b	792.17 b
P23	Catiguá MG3 P23	7.29 c	0.05 d	1.46 c	0.28 d	5.33 b	0.08 a	449.17 c	258.50 d	707.67 d
P51	Catiguá MG3 P51	10.63 a	0.19 a	2.42 a	0.73 a	4.48 c	0.04 b	463.33 b	247.00 d	710.33 d
NM	Catiguá MG3 NM	7.17 c	0.07 d	1.93 b	0.47 b	3.78 d	0.04 b	461.33 b	268.67 c	730.00 c
C62	Catuaí Amarelo IAC 62	6.35 d	0.07 d	1.46 c	0.56 b	4.36 c	0.03 b	465.33 b	342.67 a	808.00 a
C15	Catuaí Vermelho IAC 15	5.77 d	0.05 d	1.97 b	0.47 b	2.96 d	0.04 b	469.33 b	259.17 d	728.50 c
C81	Catuaí Vermelho IAC 81	6.25 d	0.06 d	1.19 c	0.45 b	5.40 b	0.05 b	473.50 a	358.33 a	831.83 a
C99	Catuaí Vermelho IAC 99	6.20 d	0.05 d	1.83 b	0.40 c	3.43 d	0.05 b	486.83 a	289.33 c	776.17 b
C	Caturra Vermelho MG 0187	5.58 d	0.05 d	1.12 c	0.47 b	5.13 b	0.03 b	468.50 b	313.67 b	782.17 b
G	Guatenano Colis MG0207	6.72 c	0.06 d	1.29 c	0.52 b	5.26 b	0.03 b	419.00 d	202.17 f	621.17 f
MN	Mundo Novo IAC 379-19	6.70 c	0.06 d	1.18 c	0.49 b	6.45 a	0.04 b	473.50 a	354.17 a	827.67 a
P	Paraíso MG1	4.96 d	0.05 d	1.38 c	0.50 b	3.59 d	0.03 b	472.50 a	276.17 c	748.67 c
PB	Pau Brasil MG1	9.48 b	0.15 b	2.43 a	0.70 a	3.93 c	0.04 b	460.50 b	267.83 c	728.33 c
S	Sacramento MG1	4.99 d	0.05 d	1.66 c	0.51 b	3.01 d	0.03 b	450.50 c	221.33 e	671.83 e
SR	San Ramon MG 0198	7.44 c	0.08 c	1.70 c	0.56 b	4.46 c	0.03 b	447.33 c	248.00 d	695.33 d
T	Topázio MG 1190	9.67 b	0.14 b	1.49 c	0.68 a	6.59 a	0.04 b	477.17 a	279.50 c	756.67 b

* Means followed by the same letter in the column belong to the same group, according to the Scott-Knott test, at 5 % of probability. [1] A: net photosynthetic rate (μmol CO_2 m^{-2} s^{-1}); gs: stomatal conductance (mmol H_2O m^{-2} s^{-1}); E: transpiration rate (mmol m^{-2} s^{-1}); CiCa: intracellular CO_2 concentration on the mesophyll under external concentration (μmol CO_2); WUE: water-use efficiency (A/E); CUE: carboxylation efficiency; Cla: Falker chlorophyll a index; Clb: Falker chlorophyll b index; ClT: Falker total chlorophyll index. [2] Representative identification of each cultivar.

location and shape (Batista et al. 2010, Baliza et al. 2012, Queiroz-Voltan et al. al. 2014). In this study, the cultivars Acaiá Cerrado MG 1474, Catiguá MG2, Catiguá MG3 P9, Catuaí Amarelo IAC 62, Paraíso MG1 and Sacramento MG1, which presented low transpiration rates (E) (Table 3), showed higher values for adaxial and abaxial epidermis thickness and a higher ratio between polar and equatorial stomatal diameter (Table 2). Higher values for this ratio indicate that the stomata take an ellipsoidal shape which reduces transpiration (Batista et al. 2010), since it favors the opening and closing dynamics, making the CO_2 assimilation more efficient (Durand et al. 2019). Moreover, the adequate stomatal transpiration control in plants sustains a better water status (DaMatta et al. 2018).

In environments with high temperatures and radiation, the increase in the spongy parenchyma thickness is an adaptation that favors the accumulation and storage of the CO_2 necessary for photosynthesis (Terashima et al. 2011, Baliza et al. 2012, Ribeiro et al. 2012, Castanheira et al. 2016). For the spongy parenchyma thickness, higher mean values were found for the cultivars Araponga MG1, Catiguá MG3 P4, Catiguá MG3 P5, Catuaí Amarelo IAC 62, Catuaí Vermelho IAC 15, Catuaí Vermelho IAC 99, Guatenano Colis MG0207, Pau Brasil MG1 and Sacramento MG1 (Table 2).

Araponga MG1, Catiguá MG3 P23, Catuaí Vermelho IAC 15, Catuaí Vermelho IAC 81 and Catuaí Vermelho IAC 99 differed from the others, as they were in the group with the highest values for characteristics such as phloem thickness and number of xylem vessels associated with the highest stomatal density, according to the Scott-Knott test (Table 3). Higher stomatal densities favor the CO_2 absorption; however, during this process, the plant loses water through transpiration (Nóia Júnior et al. 2020). The water loss in the form of steam generates a tension force, causing the plant to absorb water from the soil. The increase in the frequency of xylem vessels observed in these genotypes (Table 3) favors the hydraulic conductance and prevents embolism (Oliveira et al. 2018, Yao et al. 2020).

Regarding gas exchange, Catiguá MG1, Topázio MG1190, Catiguá MG3 P5, Catiguá MG3 P51 and Pau Brasil MG1 showed a higher stomatal conductance (gs) associated with a higher net photosynthetic rate (A), when compared to the values of the general average of the cultivars (Table 3). A higher stomatal conductance can increase the substomatic CO_2 concentration necessary for photosynthesis (Melo et al. 2009). In addition, Catiguá MG1, Mundo Novo IAC 379-19 and Topázio MG1190 showed higher water-use efficiency values. This is a desired attribute, as plants with this characteristic are more efficient in maintaining carbon assimilation during the photosynthetic process, while controlling transpiration (Ferreira et al. 2012).

Chlorophyll is the main pigment related to photosynthesis, and its content may vary among genotypes of the same species (Lee 1988, Streit et al. 2005). In this study, higher levels of chlorophyll a, b and total were observed for the Catuaí Vermelho IAC 81 and Mundo Novo IAC 379-19 cultivars, in relation to the others. On the other hand, Catuaí Amarelo IAC 62 and Caturra Vermelho MG0187 showed higher levels of chlorophyll b and total, in relation to the average of the other genotypes (Table 3).

In Figure 1, it is possible to observe the graphic dispersion of cultivars on a bidimensional plan, according to the first and second canonical variables, which represents 71.7 % of the total data variation, with formation of three groups.

Table 4 presents the correlation between the evaluated characteristics and the first two canonical variables. The contribution of characteristics to cultivar differentiation is evidenced by the highest absolute values in the canonical variables 1 and 2.

For the canonical variable 1 (CV1), the characteristics that most contributed to the cultivar variability were stomatal conductance, net photosynthetic rate and intracellular CO_2 concentration on the mesophyll under external concentration. For the canonical variable 2 (CV2), the highest correlation was observed for the characteristics chlorophyll a, b and total index (Table 4).

By observing the ranking of canonical variable scores, it was possible to identify cultivars with higher values, representing the first two canonical variables. For the first one, which corresponds to 55.40 % of the data variation, Catiguá MG3 P51, Catiguá MG1, Catiguá MG3 P5, Pau Brasil MG1 and Topázio MG1190 stood out, with higher values for stomatal conductance, net photosynthetic rate and intercellular CO_2 concentration (Figure 1; Table 4). Higher stomatal conductance scores can favor the necessary substomatal CO_2 assimilation for photosynthesis (Thioune et al. 2020). According to the canonical variable analysis, a positive correlation between these characteristics and the photosynthesis ratio was observed (Table 4). Viana et al. (2021) reported that stomatal conductance is important for differentiating coffee genotypes submitted to biotic stress. Besides,

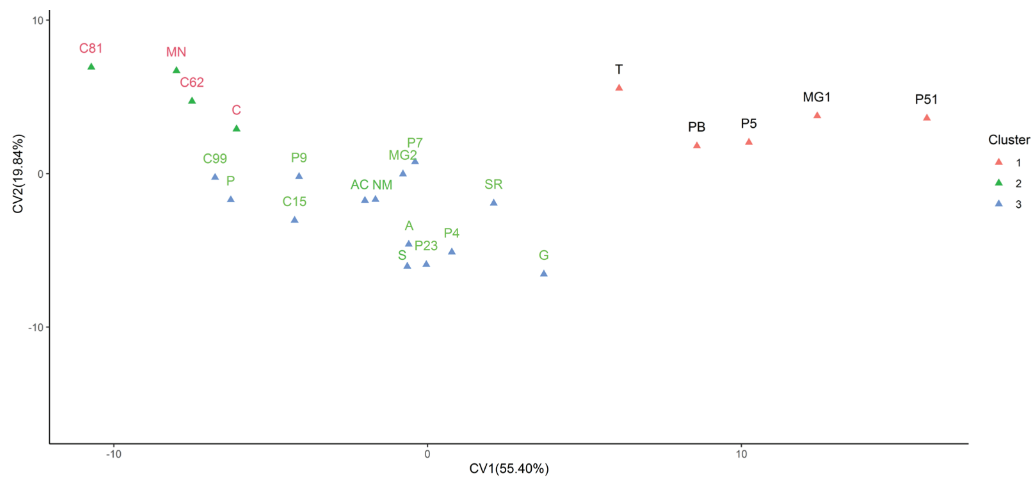

Figure 1. Dispersion of 23 *Coffea arabica* L. cultivars from the Embrapa Cerrados Germplasm Bank, in relation to the first canonical variables (CV1 and CV2). AC: Acaiá Cerrado MG1174; A: Araponga MG1; MG1: Catiguá MG1; MG2: Catiguá MG2; P4: Catiguá MG3 P4; P5: Catiguá MG3 P5; P7: Catiguá MG3 P7; P9: Catiguá MG3 P9; P23: Catiguá MG3 P23; P51: Catiguá MG3 P51; NM: Catiguá MG3 NM; C62: Catuaí Amarelo IAC 62; C15: Catuaí Vermelho IAC 15; C81: Catuaí Vermelho IAC 81; C99: Catuaí Vermelho IAC 99; C: Caturra Vermelho MG0187; G: Guatenano Colis MG0207; MN: Mundo Novo IAC 379-19; P: Paraíso MG1; PB: Pau Brasil MG1; S: Sacramento MG1; SR: San Ramon MG0198; T: Topázio MG1190.

higher values of water-use efficiency were observed for Catiguá MG1 and Topázio MG1190 (Table 3), a desirable attribute. Plants with this characteristic are more efficient to keep carbon assimilation during the photosynthetic process, controlling transpiration at the same time (Ferreira et al. 2012).

For the second canonical variable, higher chlorophyll b and total indexes were observed for Catuaí Vermelho IAC 81, Mundo Novo IAC 379-19, Topázio MG1190, Catuaí Amarelo IAC 62 and Catiguá MG1 (Tables 3 and 4; Figure 1). Chlorophyll is the main pigment related to photosynthesis, and its content may vary among the genotypes of a species (Lee 1988, Streit et al. 2005). These pigments are essential for light absorption. Chlorophyll b absorbs light on a different spectrum from chlorophyll a and is present only on antenna complexes, where it participates in the light energy transference inside the complex and from the complex to the photosystem; lower contents of this pigment can decrease the stability of some proteins in this complex (Streit et al. 2005, Voitsekhovskaja & Tyutereva 2015).

For Catuaí Amarelo IAC 62 and Catiguá MG1, higher scores for adaxial cuticle thickness were observed (Table 2). An increase in this layer may result in a higher radiation reflection and isolate internal tissues (Kumar & Tieszen 1980, Silva et al. 2004).

Among the evaluated cultivars, Topázio MG1190, Catiguá MG1 and Catiguá MG3 P51 stood out according to scores from the first and second canonical variables (Figures 2A and 2B).

Table 4. Correlation between the evaluated characteristics and the first two canonical variables (CV1 and CV2), determined in *Coffea arabica* L. cultivars from the Embrapa Cerrados Germplasm Bank.

Characteristics[(1)]	CV1	CV2
CUT	-0.139	0.262
ADE	0.237	-0.300
ABE	0.311	-0.106
PP	0.129	-0.081
SP	-0.084	-0.273
PT	-0.288	-0.224
XVD	-0.010	-0.083
NVX	-0.221	0.006
SPDED	-0.359	0.017
SD	0.248	-0.022
A	0.812	0.346
gs	0.844	0.465
E	0.442	-0.003
CiCa	0.657	0.493
WUE	0.392	0.351
CUE	0.090	-0.274
Cla	-0.300	0.503
Clb	-0.627	0.732
ClT	-0.597	0.742

[(1)] CUT: adaxial cuticle thickness; ABE: abaxial epidermis thickness; ADE: adaxial epidermis thickness; PP: palisade parenchyma thickness; SP: spongy parenchyma thickness; PT: phloem thickness between procambium and sclerenchyma; XVD: xylem diameter; NXV: number of xylem vases; SPDED: ratio between stomatal polar and equatorial diameters; SD: stomatal density; A: net photosynthetic rate; gs: stomatal conductance; E: transpiration rate; CiCa: CO_2 intracellular concentration on the mesophyll under external concentration; WUE: water-use efficiency; CUE: carboxylation efficiency; Cla: Falker chlorophyll a index; Clb: Falker chlorophyll b index; ClT: Falker total chlorophyll index.

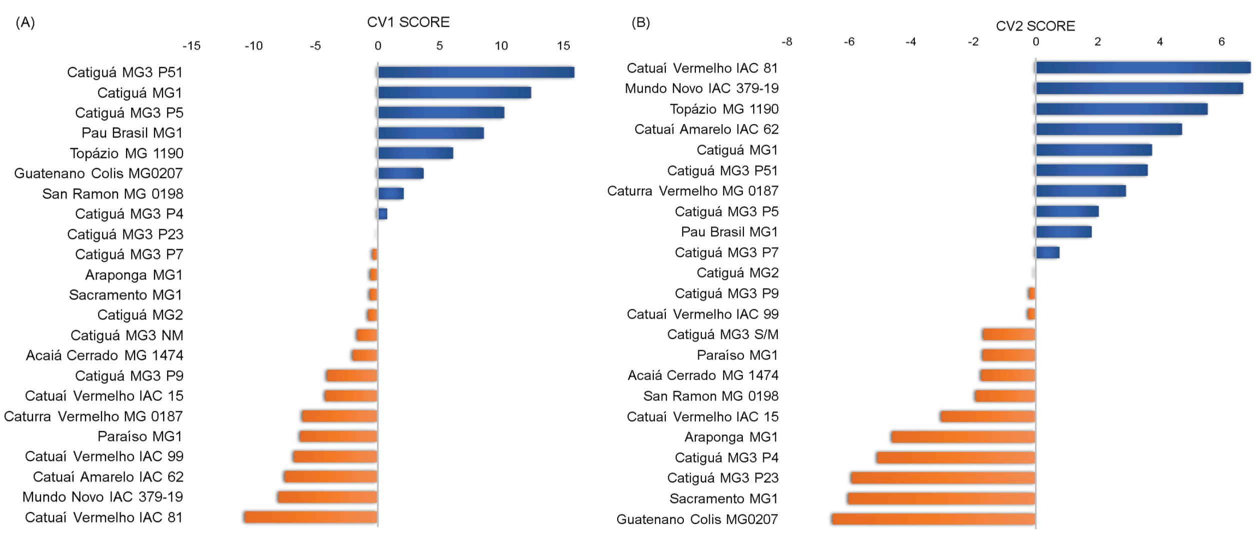

Figure 2. CV1 (A) and CV2 (B) scores for 23 *Coffea arabica* L. cultivars from the Embrapa Cerrados Germplasm Bank, regarding anatomic and physiological characteristics.

In addition, these cultivars have leaf anatomical characteristics related to adaptations to dry seasons, as isolating and protecting tissues increase. Thus, it is suggested that these cultivars have a higher capacity for physiological adaptation to the environmental conditions applied to this research and may be indicated for this region.

According to the UPGMA analysis, three distinct groups were formed when a dissimilarity of 198 was established (Figure 2). The grouping corroborated the canonical variable analysis, confirming the genotype differentiation. The first group consisted of Topázio MG1190, Catiguá MG3 P5, Pau Brasil MG1, Catiguá MG1 and Catiguá MG3 P51; the second of Catuaí Amarelo IAC 62, Caturra Vermelho MG0187, Catuaí Vermelho IAC 81 and Mundo Novo IAC 379-19; and the third of the remaining fourteen analyzed cultivars. These results show the variability among the strains of the Catiguá group, once they stood out in a distinct group for the evaluated characteristics (Figure 3).

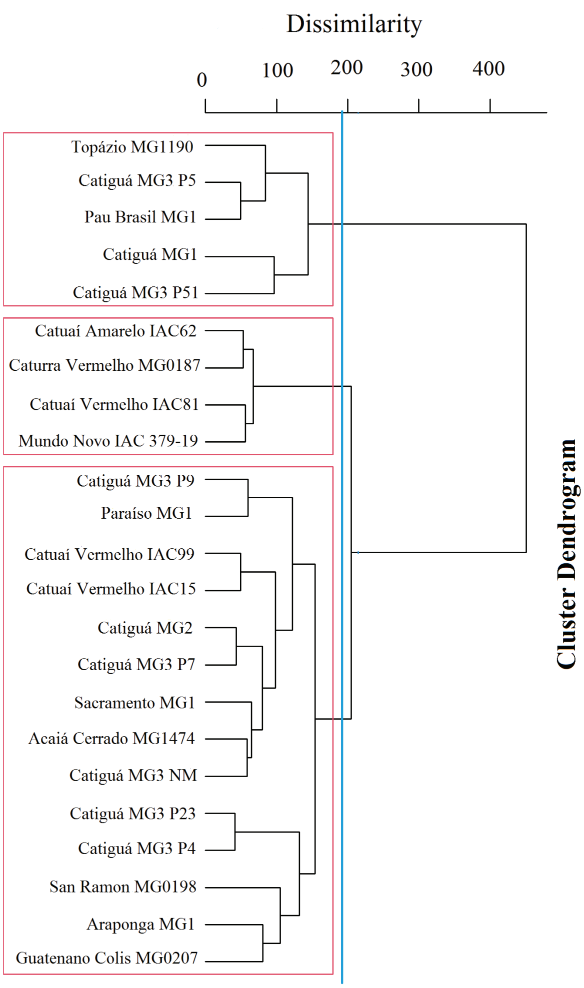

Figure 3. Dendrogram of 23 *Coffea arabica* cultivars by the unweighted pair group method using arithmetic averages (UPGMA) obtained from the generalized Mahalanobis distance.

The genetic diversity of commercial coffee is low due to the fact that it is self-pollinating (Ortega-Ortega et al. 2019). However, based on the results for more specific characteristics in the present study, a great genetic diversity was observed among the cultivars. The results demonstrated the predominance of genetic factors over environmental ones, and identified a high heritability among the evaluated characteristics. This information may help researchers in the early selection of *Coffea arabica* L. Thus, in practical terms, coffee breeding may benefit from that information. Breeders could direct divergent crossings aiming to increase the genetic variability in a breeding program which looks for materials better adapted to regions with severe dry seasons, low relative humidity and subjected to water deficit. In addition, our results may assist in the recommendation of cultivars to environments with these climatic conditions.

CONCLUSIONS

1. The analyzed *Coffea arabica* L. cultivars show differences between anatomic and physiological characteristics, indicating different adaptation strategies to the climatic conditions of the Brazilian central plateau Cerrado (Brazilian Savanna);
2. The Catiguá MG1, Catiguá MG3 P51 and Topázio MG1190 cultivars stood out, being the most suitable for hybridization in coffee genetic breeding programs;
3. Stomatal conductance, net photosynthetic rate, intracellular CO_2 concentration on the mesophyll under external concentration and Falker index of chlorophyll a, b and total are the most important characteristics for cultivar differentiation.

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