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GGE Biplot for integrating agronomic and sensory attributes in coffee cultivar selection

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Abstract: *Coffee plant breeding has developed cultivars with disease resistance, high yield, and excellent sensory quality. However, recommending cultivars for different regions requires evaluations that account for genotype × environment (G × E) interactions. This study evaluated the agronomic performance of 30 Coffea arabica cultivars in six locations in southern Minas Gerais, focusing on adaptability and phenotypic stability for yield and sensory quality using the GGE Biplot method. Traits assessed included yield, the proportion of high-sieve and mocha beans, bean density, and sensory quality. Statistical analyses involved ANOVA, the Scott-Knott test, and GGE Biplot. Two mega-environments were identified for yield and three for sensory quality. IPR 100, IAC Obatã 4739, Arara, and Catucaí 2SL demonstrated high yield, while MGS Paraíso 2 excelled in cup quality. GGE Biplot proved effective in identifying stable and adapted cultivars, reinforcing the need to integrate sensory attributes in breeding and recommendation strategies for specialty coffee production.*

Keywords: Coffea arabica*, genotype × environment interaction, South Minas Gerais, plant breeding*

INTRODUCTION

Coffee farming in Southern Minas Gerais plays a key role in both the regional and the national economy, accounting for approximately 50% of Brazil's Arabica coffee production. The region's altitudes (800 - 1,000 m), mild temperatures, and fertile soils provide ideal conditions for growing high-quality coffee. This activity supports socioeconomic development by sustaining thousands of small- and medium-sized producers, strengthening cooperatives and generating direct and indirect employment (CONAB 2024). The region's favorable edaphoclimatic conditions contribute not only to high yield but also to the sensory excellence of its coffees, reinforcing its prestige in the global market.

The growing global demand for specialty coffees has heightened the importance of sensory quality as a competitive advantage. To be classified as a specialty coffee, it must score at least 80 points on the Specialty Coffee Association (SCA) scale, which evaluates attributes such as aroma, acidity, body, and flavor (Mota et al. 2022) and provides a standardized global measurement system. This quality results from the interaction of genetic, environmental, and

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post-harvest processing factors. Cultivars such as Arara, Catiguá MG2, and MGS Paraíso 2 have excelled by combining disease resistance, high yield potential, and outstanding cup quality, often achieving scores greater than 85 points (Medeiros et al. 2021). However, these attributes can vary depending on climatic and edaphic conditions, underscoring the importance of selecting cultivars adapted to specific environments.

One of the main challenges in coffee breeding is the genotype × environment (G × E) interaction, which affects the phenotypic expression of traits such as yield and cup quality. This interaction may be simple, with consistent cultivar rankings across environments, or complex, when performance varies by location. Environmental variability - whether predictable (e.g., soil characteristics) or unpredictable (e.g., climate fluctuations) - adds complexity to the selection process (Pour-Aboughadareh et al. 2022). Therefore, identifying cultivars with both adaptability and stability is essential for ensuring consistently high performance.

Among the methodologies available to assess adaptability and stability, the GGE Biplot stands out for enabling graphical exploration of the G × E interaction, thereby facilitating the identification of superior cultivars across diverse environments. This approach has proven effective in selecting Arabica coffee cultivars that combine high yield with desirable sensory attributes under variable conditions (Silva et al. 2021, Merga et al. 2021). By integrating genotype performance with environmental responses, the GGE Biplot supports more accurate and practical decisions in cultivar selection.

Despite methodological advances, there remains a significant gap in the literature concerning the combined evaluation of yield and sensory quality using the GGE Biplot approach. Most studies address these factors independently, limiting the precision of recommendations that aim to combine agronomic performance with sensory excellence. This study aimed to evaluate the performance of *Coffea arabica* cultivars across multiple locations in Southern Minas Gerais, emphasizing adaptability and phenotypic stability for both yield and cup quality. The objective was to identify superior and stable cultivars and to delineate mega-environments favorable to high-quality coffee production, thereby enhancing recommendation strategies and informing breeding programs.

MATERIAL AND METHODS

The experiments were conducted in six locations in the Southern region of Minas Gerais. Three of them were established in experimental stations of the Agricultural Research Company of Minas Gerais (EPAMIG), located in Três Pontas, Machado, and São Sebastião do Paraíso. The others were implemented on private properties: Fazenda da Pedra (Campestre), Fazenda Oriente (Paraguaçu), and Fazenda da Grama (Itamogi). All experiments were conducted under rainfed conditions and implemented between January and February 2021, with replanting carried out in the same year to replace seedlings that did not survive. Details regarding spacing, plant stand, and altitude at each experimental site are provided in Table 1.

Table 1. Spacing, plant stand, and altitude of the six locations in the state of Minas Gerais

Location	Spacing (m)	Planting density (plants ha^{-1})	Altitude (m)
Campestre	3.5 x 0.60	4761	1073
Machado	2.8 x 0.55	6493	880
Paraguaçu	3.0 x 0.60	5555	825
Três Pontas	3.5 x 0.60	4761	905
São Sebastião do Paraíso	3.5 x 0.60	4761	1100
Itamogi	3.4 x 0.60	4902	1006

Thirty *Coffea arabica* cultivars developed by various breeding programs linked to leading Brazilian coffee research institutions were evaluated at all locations. A randomized complete block design (RCBD) with four replications was adopted, totaling 120 experimental plots per location. Each plot comprised a single row of ten plants, with the eight central plants used for evaluations. Details of the evaluated cultivars are provided in Table 2.

Yield was assessed during the 2023 and 2024 harvest seasons (first biennium). Evaluations of granulometry, grain density, and sensory quality were conducted exclusively during the 2024 harvest. Yield was determined by the total fruit yield from the plants evaluated in each plot, with the harvested mass weighed in kilograms. From each plot, a representative four-liter sample was collected, dried on a concrete patio until reaching approximately 11% moisture content, processed, and subsequently weighed. Based on these data, the yield was calculated and expressed as 60 kg $bags^{-1}$ ha^{-1} of processed coffee. The biennial average was used for statistical analyses.

Table 2. Genetic background and origin of the 30 Coffea arabica cultivars evaluated in multi-environment trials

N	Cultivar	Institution	Genetic background
1	IAC Catuaí SH_3	IAC[1]	Catuaí Vermelho IAC 46 × IAC 1110-8 (BA10)
2	IAC Obatã 4739	IAC	Obatã 1669-20 × Catuaí Amarelo
3	IAC 125 RN	IAC	Villa Sarchi CIFC 971/10 × HDT CIFC 832/2
4	IPR 100	IDR Paraná [2]	Catuai Vermelho 81 x (Catuai Vermelho 81 x IAC 1110-8 -BA-10)
5	IPR 107	IDR Paraná	Iapar 59 × Mundo Novo IAC 376-4
6	IPR 102	IDR Paraná	Catuaí Vermelho IAC 99 × Dwarf Icatu
7	IPR 103	IDR Paraná	Catuaí Vermelho IAC 99 × Dwarf Icatu
8	IPR 105	IDR Paraná	Catuaí Vermelho IAC 81 × (Catuaí Vermelho IAC×IAC 1110-8 - BA10)
9	Acauã Novo	Fundação Procafé	Mundo Novo IAC 388-17 × Sarchimor IAC 1668
10	Arara	Fundação Procafé	Villa Sarchi × HDT CIFC 832/2
11	Asa Branca	Fundação Procafé	Mundo Novo IAC 388-17 × Sarchimor IAC 1668
12	Azulão	Fundação Procafé	Catuaí Vermelho × Icatu Vermelho 785
13	Beija Flor	Fundação Procafé	Catuaí Vermelho × Icatu Vermelho 785
14	Catucaí Amarelo 24/137	Fundação Procafé	Catuaí × Icatu (híbrido natural)
15	Catucaí 2SL	Fundação Procafé	Catuaí × Icatu (híbrido natural)
16	Guará	Fundação Procafé	Catuaí vermelho x Icatu Vermelho 785
17	Japy	Fundação Procafé	Catuaí Vermelho x Icatu Vermelho 785
18	Rouxinol	Fundação Procafé	Catuaí Vermelho × Icatu Vermelho 785
19	Graúna	Fundação Procafé	Mundo Novo IAC 388-17 × Sarchimor IAC 1668
20	Catiguá MG2	Epamig/UFV/UFLA[3]	Catuaí Amarelo IAC 86 × HDT UFV 440-110
21	Paraíso MG H419-1	Epamig/UFV/UFLA	Catuaí Amarelo IAC 30 × HDT UFV 445-46
22	MGS Catucaí Pioneira	Epamig/UFV/UFLA	Catuaí Vermelho x Icatu Vermelho 785
23	MGS Aranãs	Epamig/UFV/UFLA	Icatu IAC H3851-2 × Catimor UFV 1603-215
24	MGS Paraíso 2	Epamig/UFV/UFLA	Catuaí Amarelo IAC 30 × HDT UFV 445-46
25	MGS Ametista	Epamig/UFV/UFLA	Catuaí Amarelo IAC 86 × HDT UFV 446-08
26	Pau Brasil MG1	Epamig/UFV/UFLA	Catuai Vermelho IAC 141 x HDT UFV 442-34
27	Catiguá Amarelo 6IP1FBS	Epamig/UFV/UFLA	Catuaí Amarelo IAC 86 × HDT UFV 440-110
28	MGS EPAMIG 1194	Epamig/UFV/UFLA	Catuai Amarelo x Mundo Novo
29	Catuaí Amarelo IAC 62	IAC	Mundo Novo IAC 374-19 × Caturra Amarelo IAC 476-11
30	Catuaí Vermelho IAC 144	IAC	Catuaí Amarelo IAC 476-11 x Mundo Novo IAC 374-19

HDT Timor Hybrid. [1] IAC - Instituto Agronômico de Campinas, [2] IDR-Paraná - Instituto de Desenvolvimento Rural do Paraná, [3] Epamig - Empresa de Pesquisa Agropecuária de Minas Gerais, UFV - Universidade Federal de Viçosa, UFLA - Universidade Federal de Lavras, CIFC - Centro de Investigação das Ferrugens do Cafeeiro (Portugal). Note: Most cultivars listed are resistant to coffee leaf rust (*Hemileia vastatrix*), except the last three cultivars (MGS EPAMIG 1194, Catuaí Amarelo IAC 62, and Catuaí Vermelho IAC 144), which are susceptible.

For granulometric analysis, 300 g samples of processed raw beans - free of extrinsic defects and broken beans - were used. The samples were classified by sieving, distinguishing two categories: large-screen beans (flat beans, from 19/64” to 16/64”) and mocha/peaberry beans (from 13/64” to 08/64”), in accordance with Normative Instruction No. 8 of MAPA (MAPA 2003). The beans retained on each sieve were weighed, and the results were converted into percentages to characterize the granulometric distribution of the batches. The percentages of beans retained on sieves number 16 and above are considered suitable for export. Apparent grain density was evaluated using subsamples composed exclusively of whole, defect-free beans. A 125 mL test tube was used as the volume standard, filled to the mark with beans and weighed. The values were converted to kg m^{-3}, allowing comparison among cultivars regarding bean compaction.

Sensory quality was evaluated using samples composed of eight liters of ripe fruits per plot. After washing and removing floaters and impurities, the samples were dried on sieves, initially in a thin layer (14 L m^{-2}) and subsequently in double layers, until reaching a moisture content between 10.8% and 11.2%. After 40 days of storage to standardize moisture, the beans were processed and selected using a sieve size 16 or higher, free from visual defects, and roasted according to the SCA protocol. Sensory analysis was performed by three certified Q-Graders, with five cups per sample. Scores were assigned for ten sensory attributes (acidity, balance, body, sweetness, aftertaste, fragrance/aroma, flavor, uniformity, clean cup, and overall score), and the total score was considered the final result. Samples scoring 80 points or higher were classified as specialty coffees.

Statistical analysis for all studied traits was initially conducted individually for each environment, using the linear model: $Yij = \mu + Ci + Bj + \varepsilon ij$, where: *Yij* represents the observation obtained in the plot with the i-th cultivar in the j-th block; μ is the overall mean; *Ci* and *Bj* are fixed effects of the i-th cultivar and block; and *εij* is the random effect of error associated with observation ij. After verifying the homogeneity of variances between environments using the Hartley test, the joint analysis was performed considering the six environments with the model: $Yijk = \mu + Ci + Aj + CAij + B/Ajk + \varepsilon ijk$, where: *Yijk* represents the observation of the k-th block, evaluated in the i-th cultivar and j-th environment; *μ* is overall mean; *Ci* is fixed effect of the i-th cultivar; *Aj* is fixed effect of the j-th environment; *CAij* is fixed effect of the interaction between cultivar i and environment j; *B/Ajk* is fixed effect of the k-th block within the j-th environment; and *εijk* is error associated with observation ijk.

Cultivar adaptability and stability for both yield and sensory quality were evaluated using GGE Biplot analysis, as proposed by Yan and Kang (2002). This method jointly considers the main effects of the genotypes and their interaction with the environments (G × E), through the model: $Yij - \mu - \beta j = gi_1 ei_1 + gi_2 ei_2 + \varepsilon ij$, where: *Yij* represents the expected yield of genotype i in environment j; *μ* is overall mean of observations; *βj* is main effect of environment *j*; gi_1 and ei_1 is main scores of genotype *i* and environment *j*, respectively; gi_2 and ei_e are secondary scores for genotype *i* and environment *j*, respectively; and *εij* is residual not explained by both effects. When significant differences were detected by the F-test ($p < 0.05$) in the analysis of variance, the Scott-Knott test was used to group means. All analyses were performed using R statistical software (R Core Team 2022).

RESULTS AND DISCUSSION

The joint analysis across all locations revealed significant ($p < 0.05$) effects of environment, genotype, and genotype × environment (G × E) interaction for all evaluated traits, emphasizing the importance of robust statistical approaches in supporting the recommendation of *Coffea arabica* cultivars. The GGE Biplot method was effectively applied to assess genotype adaptability and stability under varying environmental conditions, providing clear graphical outputs that supported the identification of cultivars with consistent performance across the edaphoclimatic diversity of the southern region of Minas Gerais. Coefficients of variation (CV), ranging from 1.05% to 25.43%, indicated satisfactory experimental precision and reliability of phenotypic data.

The combined analysis of means enabled the identification of genotypes combining agronomic efficiency and beverage quality. Cultivars such as IPR 100, IAC Obatã 4739, Arara, and Catucaí 2SL exhibited superior yield, with IPR 100 standing out as the sole member of the top-performing group (38.85 bags ha^{-1}), followed by a second group yielding above 33 bags ha^{-1}. These results reinforce the potential of certain genotypes for commercial exploitation under regional conditions.

Physical grain characteristics - crucial for market acceptance and industrial performance - were assessed through granulometric analyses based on MAPA (2003), which measured the proportion of flat beans retained on larger sieves and the percentage of mocha (peaberry) beans, considered grains not suitable for export. Eight groups were identified for the proportion of large flat beans (high sieve ≥ 16) and seven for mocha-type beans (% peaberry), showing a negative correlation between these traits. Cultivars IPR 107, IPR 105, and IAC Catuaí SH_3 displayed favorable combinations, with high large-screen beans (above 69%, sieve number ≥ 16) and low % Mocha (below 13%), supporting a consistent pattern where higher proportions of flat beans are associated with lower frequencies of mocha beans. Conversely, Asa Branca showed the highest % mocha (peaberry, 31.32%) and the lowest high sieve % (34.12%, sieve number > 16) (Table 3). This relationship is physiologically grounded, as mocha beans result from incomplete ovule fertilization, producing a single, oval-shaped, and denser seed (Pimenta et al. 2018). These irregular seeds can negatively impact industrial yield by compromising lot uniformity and reducing roasting and grinding efficiency. Therefore, cultivars with predominantly large, flat beans are preferred by the coffee industry for their uniformity and superior post-harvest performance (Reichel et al. 2023).

Grain density, another key physical attribute directly linked to beverage quality, varied significantly among cultivars, forming eight distinct groups, with values ranging from 673.40 to 712.14 kg m^{-3}. Densities above 650 kg m^{-3} are considered optimal, as they reflect higher concentrations of flavor precursors, better mechanical resistance, and lower defect rates

(Flores et al. 2024). In this study, all cultivars exceeded this threshold. Paraíso MG H419-1 exhibited the highest grain density (712.14 kg m^{-3}), followed closely by Arara, Graúna, Rouxinol, Catiguá MG2, Azulão, Asa Branca, and Pau Brasil MG1. The lowest values were recorded for MGS Aranãs and IPR 102, although still within the acceptable range.

Sensory analyses confirmed the high overall quality of the evaluated cultivars, with all cultivars scoring above 80 points on the SCA scale, thus qualifying as specialty coffees. Despite this general classification, four distinct sensory groups were identified. MGS Paraíso 2 achieved the highest average score (85.22), reinforcing its potential for premium markets. A second group, comprising cultivars such as Catiguá MG2, Beija-Flor, Pau Brasil MG1, IAC Catuaí SH_3, Catuaí Amarelo IAC 62, Azulão, IPR 107, among others, reached scores between 83.40 and 84.14, combining high sensory quality with agronomic and physical attributes.

The performance of *Coffea arabica* cultivars was assessed comprehensively using GGE Biplot analysis, integrating the effects of genotype, environment, and genotype × environment (G × E) interactions on both yield and sensory quality. This multivariate approach, based on principal component analysis (PCA), is widely used in breeding programs to identify genotypes with superior performance and stability across contrasting environments (Ramalho et al. 2024).

Table 3. Mean yield (bags ha^{-1}), high sieve percentage (%), beverage quality **(SCA score %),** mocha bean percentage (% Peaberry), and grain density (kg m^{-3}) of 30 Arabica coffee cultivars evaluated in six locations in Southern Minas Gerais

Cultivar	Yield (bag ha^{-1})		High Sieve (%)		Beverage quality (SCA score) %		Mocha beans (%) Peaberry		Density grain (kg m^{-3})	
IPR 100	38.85	a	65.03	c	83.17	c	15.41	c	679.76	g
IAC Obatã 4739	33.90	b	63.10	c	82.81	c	13.15	b	693.55	d
Arara	33.44	b	63.99	c	83.50	b	15.63	c	702.67	b
Catucaí 2SL	33.30	b	66.05	c	82.72	c	18.02	d	692.71	d
IPR 102	30.64	c	57.41	d	82.92	c	15.99	c	678.51	g
IPR 105	30.32	c	72.41	b	82.64	c	13.13	b	682.56	f
Graúna	30.19	c	56.00	d	83.75	b	17.00	d	705.22	b
IPR 103	30.05	c	65.80	c	83.17	c	13.53	b	688.38	e
Rouxinol	29.57	c	53.11	d	84.11	b	18.36	d	705.27	b
Catiguá MG2	28.97	c	32.47	g	84.14	b	19.17	d	704.19	b
Acauã Novo	28.82	c	38.59	f	82.19	d	20.74	e	691.94	d
MGS Aranãs	28.71	c	64.14	c	84.14	b	13.47	b	673.40	h
MGS EPAMIG 1194	28.70	c	56.36	d	83.40	b	16.31	c	685.45	f
MGS Catucaí Pioneira	28.14	c	61.32	c	83.86	b	16.47	c	688.70	e
IAC 125 RN	27.31	c	68.04	c	81.78	d	13.23	b	700.73	c
IPR 107	25.90	d	76.81	a	83.94	b	9.95	a	691.63	d
Catiguá Amarelo 6I P1FBS	25.88	d	53.98	d	82.08	d	17.83	d	699.26	c
Azulão	25.82	d	39.07	f	83.94	b	15.38	c	703.88	b
Catuaí Amarelo IAC 62	25.25	d	63.75	c	83.72	b	14.78	b	683.78	f
Guará	25.07	d	56.20	d	82.86	c	17.68	d	696.94	c
MGS Paraíso 2	25.06	d	63.18	c	85.22	a	13.99	b	693.97	d
Catucaí Amarelo 24/137	24.90	d	56.80	d	82.56	c	15.17	c	685.31	f
IAC Catuaí SH_3	24.89	d	69.14	b	83.67	b	9.82	a	693.82	d
MGS Ametista	24.86	d	55.07	d	82.58	c	14.41	b	687.05	e
Pau Brasil MG1	23.99	d	28.29	h	83.72	b	24.11	f	706.57	b
Asa Branca	22.92	d	34.12	g	81.75	d	31.32	g	706.11	b
Catuaí Vermelho 144	21.65	d	62.33	c	82.56	c	17.25	d	684.16	f
Paraíso MG H419-1	19.94	e	43.50	e	82.56	c	17.10	d	712.14	a
Japy	17.28	e	56.75	d	83.14	c	25.01	f	698.82	c
Beija Flor	14.14	f	16.60	i	84.03	b	21.38	e	697.62	c
Coefficient of variation (%)	25.43		13.50		1.18		20.05		1.05	

Means followed by the same lowercase letter in a column do not differ by the Scott-Knott test at 5% significance.

The model decomposes total variation into additive and multiplicative components, quantifying both genotypic effects and G × E interactions. For reliable interpretation, the first two principal components should explain at least 60% of the total variation (Santos et al. 2017). In this study, the biplots explained 72.49% of the variance in yield and 58.75% in sensory quality.

For yield, two mega-environments were identified (Figure 1A): the first comprising Machado, Itamogi, Três Pontas, Paraguaçu, and São Sebastião do Paraíso; and the second represented solely by Campestre. In the first, IPR 100, Arara, and Catucaí 2SL (IDs 4, 10, and 15) showed superior adaptability and yield; in the second, Arara and IAC Obatã 4739 stood out. The Average Environment Axis (AEA) (Figure 1B) positioned more productive cultivars to the right, and the distance to the AEA represented stability - with shorter distances indicating greater stability. IPR 100, Arara, IAC Obatã 4739, and Catucaí 2SL were closest to the ideal genotype (ideotype) (Figure 1C), combining high yield and stability. Arara was the most stable cultivar overall. In contrast, Beija-Flor and Paraíso MG H419-1, despite being stable, exhibited below-average yields and are therefore less recommended. These findings highlight the significant G × E interaction in trait expression and demonstrate the capacity of the GGE Biplot to differentiate genotypes and environments for yield-related decisions, consistent with Beksisa (2021), who reported similar results in Ethiopian coffee genotypes.

Environmental evaluation using the GGE Biplot (Figure 1D) revealed Itamogi as the most discriminative site (longest vector), although it showed low representativeness due to its large angular deviation from the AEA. São Sebastião do Paraíso exhibited high representativeness but limited discriminative ability. Paraguaçu showed a balance between both parameters, making it the most strategic site for yield evaluations.

Mean grouping from the combined analysis confirmed the GGE Biplot findings. IPR 100 recorded the highest yield (38.85 bags ha^{-1}), well above the Brazilian national average of 26 bags ha^{-1} (CONAB 2024), followed by IAC Obatã

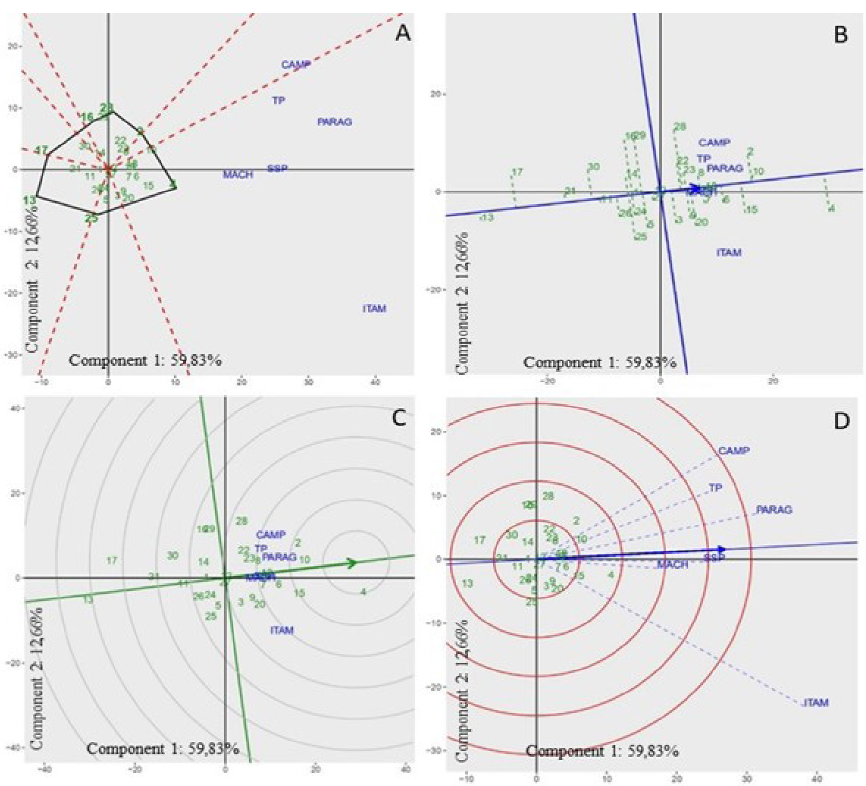

Figure 1. Integrated GGE Biplot analysis of the yield of 30 Arabica coffee cultivars evaluated in six locations. A. Delimitation of mega-environments (“Which Won Where”); B. Mean yield and stability; C. Genotype ranking; D. Discrimination and representativeness of locations.

4739, Arara, and Catucaí 2SL, with yields above 33 bags ha^{-1}. These genotypes are strong candidates for commercial recommendation in southern Minas Gerais. IPR 100, released in 2012, combines high yield with drought tolerance and resistance to *Meloidogyne* spp., including *M. paranaensis*, *M. incognita*, and suppression of *M. exigua* (Sera et al. 2017, Barrantes et al. 2020). Arara, also released in 2012, shows high yield, superior cup quality, large beans, and rust resistance conferred by Sarchimor-derived genes (Reichel et al. 2023). Its vegetative vigor enhances phenotypic plasticity and environmental adaptation. Arara and IAC Obatã 4739 share a common progenitor (Obatã IAC 1669-20 crossed with Catuaí Amarelo), which may explain their consistent performance across environments (Filla et al. 2024, Oliveira et al. 2025). Catucaí 2SL, a natural hybrid of Catuaí and Icatu, also performed well due to its robustness and abiotic stress tolerance (Carvalho et al. 2012).

For sensory quality, the GGE Biplot (Figure 2A) identified three mega-environments: (1) Itamogi and Paraguaçu; (2) Campestre; and (3) São Sebastião do Paraíso, Três Pontas, and Machado. Catuaí Vermelho IAC 144, MGS Paraíso 2, and Beija-Flor were the best adapted to their respective mega-environments. However, Catuaí Vermelho IAC 144 and Beija-Flor, despite their adaptability, showed instability and below-average cup scores (Figures 2B and 2C), limiting their suitability for specialty markets. In contrast, MGS Paraíso 2 exhibited high stability and scored consistently above 85 points in all environments, qualifying as ‘excellent’ according to SCA standards. These results confirm findings from Malta et al. (2021) and Voltolini et al. (2025), which highlighted MGS Paraíso 2’s potential for specialty coffee.

Environmental analysis for sensory traits (Figure 2D) showed Itamogi as highly discriminative but poorly representative, making it unreliable for broader recommendations. Campestre combined high discrimination with strong representativeness, making it an ideal site for sensory evaluations. Machado, on the other hand, performed poorly in both parameters.

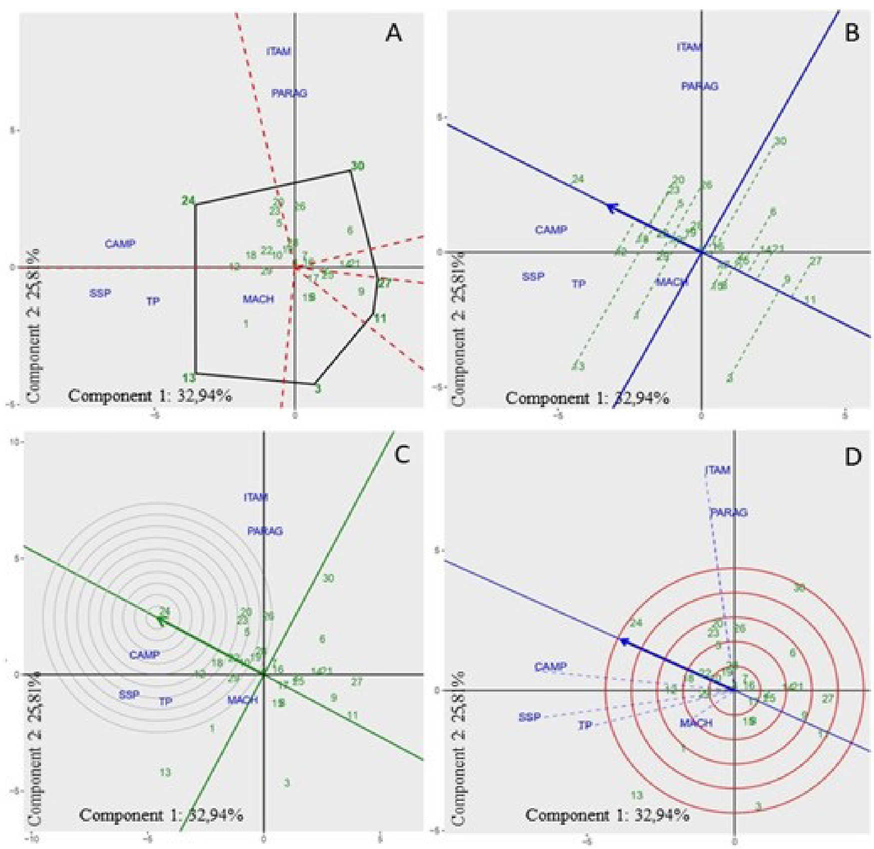

Figure 2. Integrated GGE Biplot analysis of sensory and beverage quality of 30 Arabica coffee cultivars evaluated in six locations. A. Delimitation of mega-environments (“Which Won Where”); B. Mean performance and stability; C. Genotype ranking; D. Discriminative ability and representativeness of locations.

Although the first two components explained only 58.75% of the sensory quality variance - slightly below the ideal threshold, this value is still considered acceptable, particularly for complex and subjective traits. According to Santos et al. (2017), the explained variance varies depending on the genetic architecture of the trait and the magnitude of the G × E interaction. The inclusion of sensory traits in GGE Biplot analyses remains rare but is increasingly necessary, as emphasized by Barbosa et al. (2020), considering its relevance to value addition in specialty markets.

Altogether, the identification of two mega-environments for yield and three for sensory quality reflects the strong environmental sensitivity of beverage traits and validates the use of the GGE Biplot for integrated cultivar recommendations. This tool elucidates cultivar behavior across environments and assists in the identification of strategic testing sites and genotypes with broad or specific adaptability, thereby supporting more precise and sustainable coffee breeding strategies.

DATA AVAILABILITY

The datasets generated and/or analyzed during the current research are available from the corresponding author upon reasonable request.

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