

Path analysis aiding the early selection of Conilon coffee for multiple environments

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Received: June 27, 2025 | Accepted: Jan. 20, 2026

Section Editor: Christian Cilas 

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How to cite: Senra, J. F. B., Rodrigues, W. N., Colodetti, T. V., Ferreira, A., Esposti, M. D. D., Milheiros, I. S., Silva, T. S. and Ramos, I. B. (2026). Path analysis aiding the early selection of Conilon coffee for multiple environments. *Bragantia*, 85, e20250128. <https://doi.org/10.1590/1678-4499.20250128>

ABSTRACT: This study aimed to evaluate the genetic relationships between morphological traits and the yield of Conilon coffee to identify key attributes for early selection using path analysis. The experiment followed Federer's augmented block design, with six blocks and five plants per plot, established in two environments: Alegre, at 700 m of altitude, and Cachoeiro de Itapemirim, at 140 m altitude, both in Espírito Santo State, Brazil. A total of 112 genotypes were assessed, using eight common cultivars as controls, at six, 12, and 18 months after planting. The genetic values for crop yield were obtained using mixed model methodology and evaluated through Deviance analysis. Correlation, collinearity diagnosis, and path analysis were performed between morphological traits and productivity. The five best genotypes for cultivation in both locations were T3, 28, 69, 100, and 107. The genotypes 28, T3, 69, 107, and 106 stood out in Alegre, while T3, 28, 69, 100, and 107 were the top-performing in Cachoeiro de Itapemirim. It was inferred that the genotype-environment interaction for productivity may be simple. The multicollinearity analysis played a crucial role in eliminating traits that inflated the model. For the early selection, breeding programs should prioritize the number of leaves, NDVI readings, and measurements of canopy diameter and height.

Key words: breeding programs, genotype-environment interaction, mixed model, multicollinearity analysis, selection.

INTRODUCTION

Coffee is one of the most popular and consumed beverages in the world and a valuable commodity in many Asian, African, and Latin American countries. The genus *Coffea* is a Eudicotyledoneae of the Rubiaceae family, which has more than 130 recorded species (Davis and Rakotonasolo 2011). Among these, only *Coffea arabica* and *Coffea canephora* are currently economically important, while the others are valuable sources of genetic variability for genetic breeding programs (Mistro et al. 2019). *Coffea canephora* is an allogamous species with gametophytic self-incompatibility (Souza et al. 2021).

Brazil is the second largest producer of Conilon coffee in the world, and the state of Espírito Santo is the main national producer, responsible for 64% of the production (Conab 2022). To achieve higher levels of production and crop yield, scientific research on phytotechnics and genetic breeding of the *C. canephora* has been developed in Brazil, especially for the state of Espírito Santo. In response to these challenges, significant advances have been made by genetic breeding in Brazil. Genetic breeding research institutes in Brazil have developed 45 *C. canephora* cultivars (Souza et al. 2025), the majority of which are intended for the two largest Conilon coffee-producing states in the country, Espírito Santo and Rondônia.

In Espírito Santo state, primary research on Conilon coffee is conducted by Instituto Capixaba de Pesquisa, Assistência Técnica e Extensão Rural (Incaper), whereas in Rondônia it is led by Empresa Brasileira de Pesquisa Agropecuária (Embrapa).



For Espírito Santo, Incaper has developed 14 cultivars, comprising two seed-propagated varieties, 11 clonal cultivars, and one rootstock exhibiting resistance to root-knot nematodes (Souza et al. 2025). In Rondônia, the principal genetic resources include cultivars developed by Embrapa's breeding program (Rocha et al. 2021), as well as clones selected by local producers (Espindula et al. 2022).

The application of early selection techniques is essential to accelerate the gains of breeding programs, and among these techniques, path analysis stands out. Path analysis makes it possible to study the relationships between traits by estimating coefficients that characterize the influence that one trait exerts on another (Azevedo et al. 2016). These effects can be broken down into a simpler system that explains the relationships between variables (Teixeira et al. 2012).

The evaluation of the initial vegetative performance of coffee plants is a useful tool for the early selection and identification of genotypes with greater environmental adaptation and, consequently, higher expected yield potential in future harvests (Carvalho et al. 2022, Romano et al. 2022). Identifying the most relevant morphological traits for selecting the most responsive materials is one of the main goals of coffee breeding programs, since the development of a cultivar is a costly and time-consuming process (Filla et al. 2023). Consequently, identifying the most relevant morphological traits provides greater reliability, accuracy, and efficiency in developing selection indices and identifying cultivars with higher yield potential for each environment (Filla et al. 2023).

Path analysis partitions the correlation coefficients of the predictor variables into their direct and indirect impacts on the dependent variable, identifying the effect on the trait of interest, and determining which traits should be targets of selection to improve efficiency (Tolera et al. 2024). Due to multicollinearity, the variances associated with the path analysis coefficients can reach high values, overestimating the biological effects in the research. These discrepant values show unreliable estimates lacking biological meaning. The interpretation of direct and indirect effects estimated in path analyses with a high degree of multicollinearity should be avoided, because they do not accurately represent real cause-and-effect relationships (Toebe and Cargnelutti Filho 2013).

It has been demonstrated that the evaluation of morphological traits can be effectively applied to differentiate Conilon coffee (*Coffea canephora*) genotypes (Ferrão et al., 2021). Consequently, these traits can also be used to identify materials with high yield potential. In a study on Arabica coffee, the length of plagiotropic branches and the number of nodes were found to be useful for the early selection of genotypes with higher production potential (Filla et al. 2023). Specifically for *C. canephora*, a study employing path analysis indicated that the number of plagiotropic branches and the number of rosettes per productive branch have the greatest direct effect on the yield of processed coffee (Spinelli et al. 2018).

Based on the literature, it is hypothesized that morphological traits evaluated during the early developmental stages of Conilon coffee plants may reveal traits associated with higher yield potential. Therefore, identifying these key traits through path analysis may enhance the efficiency of early selection in Conilon coffee breeding programs. Given the need to shorten the selection cycles of breeding programs of *C. canephora*, this study aimed to evaluate the genetic relationships between morphological traits and the crop yield of Conilon coffee to identify key attributes for early selection using path analysis.

MATERIALS AND METHODS

The experiment was conducted in two environments located in different municipalities in the southern region of the state of Espírito Santo, Brazil. These environments were selected to represent distinct altitude levels. The high-altitude environment was established in the municipality of Alegre (20°52'0"S, 41°28'0"W, 700 m a.s.l.). The climate of the site is classified as Cwa, humid subtropical with dry winter and rainy summer, according to the Köppen climate classification. The mean annual temperature is 22°C, with an average annual precipitation of about 1,400 mm and an estimated annual water deficit of around 100 mm. The topography is undulating, and the soil is classified as a Typic Hapludox. The low-altitude environment was installed in Cachoeiro de Itapemirim (20°45'22.9"S, 41°16'52.4"W, 140 m a.s.l.). The climate is also classified as Cwa, with rainy summers and dry winters, according to the Köppen classification. The mean annual temperature is 23°C, the mean annual precipitation is approximately 1,200 mm, and the annual water deficit reaches about 150 mm. The topography is undulating, and the soil is classified as a dystrophic Red-Yellow Latosol.

The genotypes of *C. canephora* used in this study belong to the Active Germplasm Bank (AGB) of the Incaper. These genotypes come from different origins, being part of commercial varieties, stages of the breeding program or preserved in germoplasm banks. A group of genotypes was selected from crops above 600 meters in altitude (transitional for the agroclimatic zoning for the species), originated from seminal seedlings or vegetative propagation with more than 30 years of implementation (Table 1).

Table 1. Identification and origin of the evaluated genotypes of Conilon coffee.

Type	Genotypes	Number of genotypes	Origin
New treatments	1, 2, 4, 5, 6, 7, 8, and 9	8	Previous selection in Alegre, ES
	10, 11, 12, 13, 14, 15, 16, 17, 18, and 19	10	Previous selection in Iúna, ES
	20, 21, 22, 23, 24, 25, 26, 27, 28, 29, 30, and 31	12	Previous selection in Jerônimo Monteiro, ES
	32, 33, 34, 35, 37, 38, 39, 40, 41, 42, 43, 44, 45, 46, 47, 48, 49, 50, 51, 52, 53, 54, 55, 56, and 57	25	Previous selection in Muniz Freire, ES
	59, 62, 63, 65, 66, 67, 68, 69, 70, 71, 72, 73, 75, 76, 78, 79, 80, 81, 82, 83, 84, 85, 86, 87, 88, 89, 90, 91, 92, 93, 94, 95, 96, 97, 98, 99, 100, 101, 102, 103, 104, 105, 106, 107, 108, 109, 110, 111, and 112	49	Incaper breeding program
Controls	T1, T2, T3, T4, and T5	5	Elite clones from commercial varieties ¹ : 102, 105, 108, 201, and 405
	T6, T7, and T8	3	Arabica coffee tree cultivars ² : Catucaí 24/137, Catucaí 785/15 and Arara

¹Popularly known as 23/93, 02/86 and A1 (available as part of the cultivar "ES8112 Diamante"), LB1 (available as part of the cultivar "ES8122 Jequitibá"), and 405 (available as part of the cultivar "ES8143 Marilândia"); ²cultivars of *Coffea arabica* L. used as checks for the experimental design.

The 112 genotypes were distributed in each environment following a Federer's augmented block design, with six blocks and five plants per experimental plot. Eight common cultivars were used as controls in each environment (Table 1).

Before planting, composite soil samples were collected from the 0–20-cm layer in each experimental site for chemical analysis. In Alegre, the soil showed pH (H₂O) = 5.67, P = 13.9 mg·dm⁻³, K = 145.4 mg·dm⁻³, Ca²⁺ = 4.29 cmol_c·dm⁻³, Mg²⁺ = 1.29 cmol_c·dm⁻³, Al³⁺ = 0 cmol_c·dm⁻³, sum of bases = 5.99 cmol_c·dm⁻³, effective cation-exchange capacity (t) = 5.99 cmol_c·dm⁻³, and cation-exchange capacity at pH 7 (T) = 8 cmol_c·dm⁻³. In Cachoeiro de Itapemirim, the soil showed pH (H₂O) = 7.07, P = 16.1 mg·dm⁻³, K = 223.4 mg·dm⁻³, Ca²⁺ = 3.75 cmol_c·dm⁻³, Mg²⁺ = 1.20 cmol_c·dm⁻³, Al³⁺ = 0 cmol_c·dm⁻³, sum of bases = 5.54 cmol_c·dm⁻³, t = 5.54 cmol_c·dm⁻³, and T = 5.54 cmol_c·dm⁻³. The crops were established in December 2020, with a spacing of 2.5 m between rows and 1 m between plants. Soil, phytosanitary, and crop management practices were performed according to the species' requirements and current recommendations (Ferrão et al. 2019).

To following morphophysiological traits were evaluated along the development of the coffee plants: plant height (cm) was measured as the length of the largest orthotropic stem, using a graduated ruler; stem diameter (mm) was measured at the intermediate position of the fist internode over soil level, using a digital caliper (0.01 mm); canopy diameter (cm) was measured as the greatest distance from the ends of plagiotropic branches of opposite sides of the canopy on both directions, perpendicular and parallel to the crop lines, with a graduated ruler, and the average diameter was calculated using both measurements; number of leaves and number of plagiotropic branches (units) were counted; normalized difference vegetation index (NDVI) was measured on two leaves of the third or fourth pairs from the end of a plagiotropic branches, from the middle position of the plant, using a portable sensor (PlantPen, NDVI-300, Photon Systems Instruments PSI, Drásov, Czech Republic); length and width of leaves (cm) were measured from the largest longitudinal and transversal dimensions of the leaf blade, sampled with the same methodology described for NDVI, using a graduated ruler; unitary leaf area (cm²) was estimated using a non-destructive method, using the leaf dimensions with the equation by Schmidl et al. (2015); total leaf area (cm²) was estimated by the product of number of leaves and unitary leaf area; canopy height (cm) was measured with a graduated ruler, considering the distance of insertion of the lowest plagiotropic branches and the apex of the orthotropic stem;

canopy volume (m³) was estimated using the average canopy diameter and height (Favarin et al. 2002); leaf area index (m²·m⁻²) was estimated using the canopy volume (Favarin et al. 2002); and soil plant analysis development (SPAD) index was obtained by measuring the right and left mesophyll of leaves, following the same sampling used for NDVI, using a portable chlorophyll meter (SPAD-502 Plus, Konica Minolta, Tokyo). The traits were predominantly evaluated at six, 12, and 18 months after planting, totaling a set of 46 variables under evaluation (Table 2).

Table 2. Combination of morphophysiological traits and evaluation periods that composed each variable.

Traits	Evaluation period (months)		
	6	12	18
Plant height (PHEI)	PHEI-6	PHEI-12	PHEI-18
Stem base diameter (STBD)	SDIA-6	SDIA-12	SDIA-18
Canopy diameter parallel to the crop lines (CDPL)	CDPL-6	CDPL-12	CDPL-18
Canopy diameter perpendicular to the crop lines (CDPR)	CDPR-6	CDPR-12	CDPR-18
Average canopy diameter (AVCD)	AVCD-6	AVCD-12	AVCD-18
Number of leaves (NLEA)	NLEA-6	NLEA-12	NLEA-18
Normalized difference vegetation index (NDVI)	NDVI-6	NDVI-12	NDVI-18
Leaf length (LLEN)	LLEN-6	LLEN-12	LLEN-18
Leaf width (LWID)	LWID-6	LWID-12	LWID-18
Canopy height (CHEI)	CHEI-6	CHEI-12	CHEI-18
Unitary leaf area (ULAR)	ULAR-6	ULAR-12	ULAR-18
Total leaf area (TLAR)	TLAR-6	TLAR-12	TLAR-18
Canopy volume (CVOL)	CVOL-6	CVOL-12	CVOL-18
Leaf area index (LAIN)	LAIN-6	LAIN-12	LAIN-18
Soil-plant analysis development (SPAD)	-	SPAD-12	SPAD-18
Number of plagiotropic branches (NPBR)	-	NPBR-12	NPBR-18

At the end of the reproductive cycle 2023–2024, after ripening, the fruits were harvested and processed, and the crop yield was calculated and expressed as quantify of coffee bags (60 kg) produced per area (ha).

The genetic parameters were estimated using the restricted maximum likelihood method and the best unbiased linear prediction (REML/BLUP) (Resende 2007), applying the Eq. 1:

$$y = X_m + Z_g + Q_p + T_i + W_b + e \quad (1)$$

where: y : the data vector; m : the vector of the effects of the measurement-repetition-environment combinations (assumed to be fixed) added to the overall mean; g : the vector of genotypic effects (assumed to be random); p : the vector of the permanent environmental effects of the plots (random); i : the vector of the effects of the interaction between genotypes and locations; b : the vector of block effects (random); e : the vector of errors or residuals (random).

The capital letters represent the incidence matrices for the referred effects.

Based on this model, the following components were estimated: genetic variance (σ_g^2); permanent environmental variance (σ_{perm}^2); variance of the interaction between genotypes and environments (σ_{int}^2); environmental variance between blocks (σ_b^2); residual variance (σ_e^2); phenotypic variance (σ_{phen}^2); broad-sense heritability of individual plots (h^2); broad-sense heritability of the mean of the genotypes (h_{mg}^2); accuracy of genotype selection ($\overline{r_{gg}}$); individual repeatability (r); coefficient of determination of permanent plot effects (c_{perm}^2); coefficient of determination of the effects of the interaction between genotypes and environments (c_{int}^2); coefficient of determination of the effects of the blocks (c_b^2); genotypic correlation across environments (r_1^2); genotypic coefficient of variation (CV_g); residual coefficient of variation (CV_e); relative coefficient of

variation (CV_p); and overall mean (μ). The significance of the random effects of the model was tested by deviance analysis, at one degree of freedom by the X^2 distribution, using the likelihood ratio test (LRT) (Eq. 2):

$$LRT = -2(\text{Log}L - \text{Log}LR) \quad (2)$$

where: $\text{Log}L$: the logarithm of the maximum (L) of the restricted likelihood function of the full model; $\text{Log}L_R$: the logarithm of the maximum (LR) of the restricted likelihood function of the reduced model (without the effect being tested).

The estimation of the REML/BLUP parameters and the significance of random effects were performed via deviance analysis, using the Selegen software (Resende 2016).

Subsequently, an analysis of the correlation between the genetic value of the crop yield of the genotypes and the phenotypic traits described in Table 2 was done for each environment. The significance of the correlation was analyzed by the t-test, using the software GENES (Cruz 2016). Path analysis was performed between the phenotypic traits (Table 2) and the genetic value of the crop yield. For this purpose, a collinearity analysis was performed to discard traits that presented a variance inflation factor (VIF) greater than 10. These analyses were performed using the R software (R Core Team 2022).

RESULTS

The magnitude of the genetic parameters and variance components showed a substantial viability of the prediction of genetic values for the crop yield of the genotypes (Table 3). The source of variation of genetic origin was superior over the residual one, resulting in a considerable value for the relative coefficient of variation. The selective accuracy of 78.51% indicates a high reliability of a selection of genotypes for crop yield and indicates that this variable could be applied as a dependent variable in the path analysis.

Table 3. Variance components, genetic parameters, and phenotypic means for crop yield (bags·ha⁻¹) of 112 genotypes of *Coffea canephora* cultivated in two environments: Alegre (Espírito Santo, Brazil, 700 m altitude) and Cachoeiro de Itapemirim (Espírito Santo, Brazil, 140 m altitude).

Component	Value	Component	Value
σ_g^2	228.2894	c_{perm}^2	0.0036
σ_{perm}^2	2.9563	c_{int}^2	0.0323
σ_{int}^2	26.2910	c_b^2	0.0557
σ_b^2	45.3921	r_l^2	0.8967
σ_e^2	511.6842	CV_g	35.5579
σ_{phen}^2	814.6131	CV_e	22.1064
h^2	0.2802	CV_r	1.6085
h_{mg}^2	0.6165	μ	42.4920
r_{gg}	0.7851	μ_A	40.2834
r	0.3161	μ_C	44.7005

Genetic variance accounts for a proportion of the phenotypic variance, relative to the variance attributed to block effects, interaction, and permanent environment factors. Heritability exhibited a moderate value, higher than the coefficients of determination. This is consistent with the Deviance analysis (Table 4), which indicates that the genetic effect was significant, while the other effects were not. The performance correlation was approximately 0.90, a notably high value, highlighting that the most productive genotypes in the Alegre also performed well in Cachoeiro de Itapemirim. This suggests that genotype-environment interaction was relatively simple (Suppl. Mat.). A difference of 4 bags·ha⁻¹ was observed between the two studied environments, with higher crop yield observed in Cachoeiro de Itapemirim. However, it is noteworthy that estimated yields higher than 70 bags·ha⁻¹ were obtained in both locations (Suppl. Mat.).

Table 4. Deviance and likelihood ratio test (LRT) for the crop yield of 112 genotypes of *Coffea canephora* cultivated in two environments: Alegre (Espírito Santo, Brazil, 700 m altitude) and Cachoeiro de Itapemirim (Espírito Santo, Brazil, 140 m altitude).

Effect	Deviance	LRT	Variance components	Coefficient of determination	p-value
Genetic	4,118.10	26.73	228.2894	0.2802	2.3396×10 ⁻⁷
Permanent	4,091.37	0.00	2.9563	0.0036	1.0000
Interaction	4,092.28	0.91	26.2910	0.0323	0.3401
Block	4,104.76	13.39	45.3921	0.0557	2.5297×10 ⁻⁴
Full Model	4,091.37				

The correlation analysis between morphophysiological traits and the crop yield identified 14 traits with significant correlation in the municipality of Alegre and 38 in the municipality of Cachoeiro de Itapemirim (Tables 5 and Table 6). These simple correlations suggested that the traits under study have the potential to explain the yield, these significant correlations ranged from weak to low in Alegre (0.175–0.2839) and from weak to moderate in Cachoeiro de Itapemirim (0.1988–0.5045). These differences in number and magnitude of significant correlations between municipalities indicated a strong influence of the local environmental conditions on the expression of morphophysiological traits and their association with the crop yield, which is expected as this is a complex trait, typically controlled by multiple genes and influenced by several possible interactions. However, the large number of correlated traits raises concerns about possible collinearity problems. Collinearity analysis conducted in both environments allowed to discard traits with VIF values exceeding 10. This process allowed to select 30 promising traits in the municipality of Alegre and 29 in Cachoeiro de Itapemirim (Tables 7 and Table 8).

Path analysis identified traits with significant associations in both environments (Table 9 and Fig. 1). In Alegre, traits SDIA-6, LWID-6, and NLEA-12 presented negative and significant associations at the 5% level, while trait NLEA-18 showed a positive and significant association at the 0.1% level. In Cachoeiro de Itapemirim, traits CDPR-6, CHEI-6, NDVI-12, and NLEA-18 presented positive associations, with trait NDVI-12 being significant at 5% level and the others at the 0.1% level. These results highlight the potential of evaluating the number of leaves on Conilon coffee trees, 18 months after planting, as a valuable method for early identification of the most productive genetic materials.

Table 5. Morphophysiological traits with significant correlation with the crop yield, by the t-test, in the municipality of Alegre, Espírito Santo, Brazil (700 m altitude).

Traits	Covariance	Correlation	p-value
NLEA-18	1,047,0151	0.2839	0.030400
CDPL-18	64.0645	0.2726	0.004390
AVCD-18	60.9476	0.2701	0.047460
LLEN-12	5.7021	0.2507	0.008666
CDPR-18	57.8308	0.2487	0.009209
ULAR-12	49.1158	0.2325	0.014812
AVCD-6	26.1585	0.2283	0.016670
CDPR-6	25.5635	0.2136	0.025057
SPAD-18	0.2153	0.2103	0.027402
NPBR-18	0.5983	0.2103	0.027402
CDPL-12	43.0843	0.2015	0.034527
CDPL-6	26.7535	0.1876	0.049108
LAIN-18	51,365.1089	0.1875	0.049253
NLEA-6	50.7518	0.1875	0.049187

Table 6. Morphophysiological traits with significant correlation (Corr.) with the crop yield, by the t-test, in the municipality of Cachoeiro de Itapemirim, Espírito Santo, Brazil (140 m altitude).

Trait	Covariance	Corr.	p-value	Trait	Covariance	Corr.	p-value
SDIA-18	83.0073	0.5045	0.000000	NPBR-12	64.0656	0.3470	0.000279
LAIN-18	121,184.8000	0.4891	0.000000	PHEI-12	61.9401	0.3218	0.000731
AVCD-12	125.8570	0.4606	0.000002	LLEN-18	69.8077	0.3175	0.000858
CVOL-12	0.4906	0.4581	0.000002	LLEN-12	9.0012	0.3169	0.000876
LAIN-12	1.3634	0.4581	0.000002	NLEA-6	122.8626	0.3064	0.001282
CDPL-12	129.3773	0.4560	0.000002	CDPL-18	32.6130	0.3062	0.001292
NLEA-18	2,145.7800	0.4465	0.000003	AVCD-6	37.2554	0.3011	0.001546
CDPR-12	122.3367	0.4405	0.000004	CHEI-6	35.9112	0.2946	0.001934
AVCD-18	106.7383	0.4143	0.000016	CHEI-12	44.9092	0.2824	0.002928
CDPR-18	112.7093	0.4099	0.000019	ULAR-12	58.7115	0.2718	0.004158
TLAR-12	162,177.8000	0.4084	0.000020	SPAD-12	27.9409	0.2515	0.007907
CDPL-18	100.7672	0.3918	0.000043	TLAR-6	7,751.6820	0.2477	0.008869
SPAD-18	0.4872	0.3852	0.000057	PHEI-18	47.4250	0.2426	0.010331
NPBR-18	1.3541	0.3852	0.000057	TLAR-18	41.9826	0.2419	0.010549
CDPR-6	53.4951	0.3830	0.000063	CHEI-18	4.3541	0.2342	0.013265
NLEA-12	1,821.9310	0.3806	0.000070	SDIA-6	4.6263	0.2318	0.014199
CVOL-6	0.0403	0.3780	0.000078	NDVI-12	0.0629	0.2125	0.024507
LAIN-6	0.1110	0.3721	0.000101	CVOL-18	30.3511	0.2064	0.028867
SDIA-12	41.7053	0.3714	0.000104	LWID-12	2.3877	0.1988	0.035272

Table 7. Variance inflation factor (VIF) of the morphophysiological traits for path analysis in the municipality of Alegre, Espírito Santo, Brazil (700 m altitude).

Traits	VIF	Traits	VIF	Traits	VIF
PHEI-18	8.1122	SDIA-6	4.6335	SPAD-12	2.4793
DCPR-12	7.5004	PHEI-12	4.4664	CDPR-6	2.4481
CDPL-12	7.3091	NLEA-6	4.0373	LWID-18	2.4444
NPBR-12	6.4622	CHEI-18	3.6155	LLEN-12	2.4378
NLEA-12	6.0723	ULAR-18	3.1265	NDVI-12	2.4144
NLEA-18	5.9694	CHEI-12	3.0480	SDIA-18	2.2003
CDPL-18	5.7462	CDPL-6	2.6119	LLEN-6	2.1819
LLEN-18	5.2647	PHEI-6	2.5986	NDVI-18	2.1184
SDIA-12	4.9866	LWD-12	2.5790	LWID-6	1.8302
TLAR-18	4.9005	NDVI-6	2.4874	CHEI-6	1.7571

Table 8. Variance inflation factor (VIF) of the morphophysiological traits for path analysis in the municipality of Cachoeiro de Itapemirim, Espírito Santo, Brazil (140 m altitude).

Traits	VIF	Traits	VIF	Traits	VIF
CDPL-18	7.5970	LWID-12	4.2033	ULAR-18	2.5878
NLEA-6	6.9227	LLEN-18	4.0602	CHEI-12	2.4432
CDPR-18	6.0782	PHEI-12	3.9675	LLEN-6	2.0721
NLEA-12	5.9935	NLEA-18	3.7501	NDVI-12	1.9095
SDIA-6	5.7812	PHEI-6	3.6575	NDVI-6	1.8941
SDIA-12	5.4235	CDPL-6	3.1069	LWID-18	1.8043
LLEN-12	5.2970	CHEI-18	3.0909	LWID-6	1.7617
NPBR-12	5.1453	SDIA-18	3.0637	CHEI-6	1.6891
CDPR-6	4.8110	TLAR-18	3.0195	NDVI-18	1.4174
AVCD-12	4.7556	SPAD-12	2.8933		

Table 9. Path analysis of the morphophysiological traits with significant association with crop yield of 112 genotypes of *Coffea canephora* cultivated in two environments: Alegre (Espírito Santo, Brazil, 700 m altitude) and Cachoeiro de Itapemirim (Espírito Santo, Brazil, 140 m altitude).

Environment	Traits	Estimate	Standard error	Z-value	p-value
Alegre	SDIA-6	-3.52	1.536	-2.292	0.022
	LWID-6	-1.94	0.865	-2.242	0.025
	NLEA-12	-0.015	0.007	-2.041	0.041
	NLEA-18	0.022	0.007	3.025	0.002
Cachoeiro de Itapemirim	CDPR-6	0.557	0.194	2.879	0.004
	CHEI-6	0.399	0.125	3.187	0.001
	NDVI-12	126.028	54.888	2.296	0.022
	NLEA-18	0.018	0.005	3.835	0.000

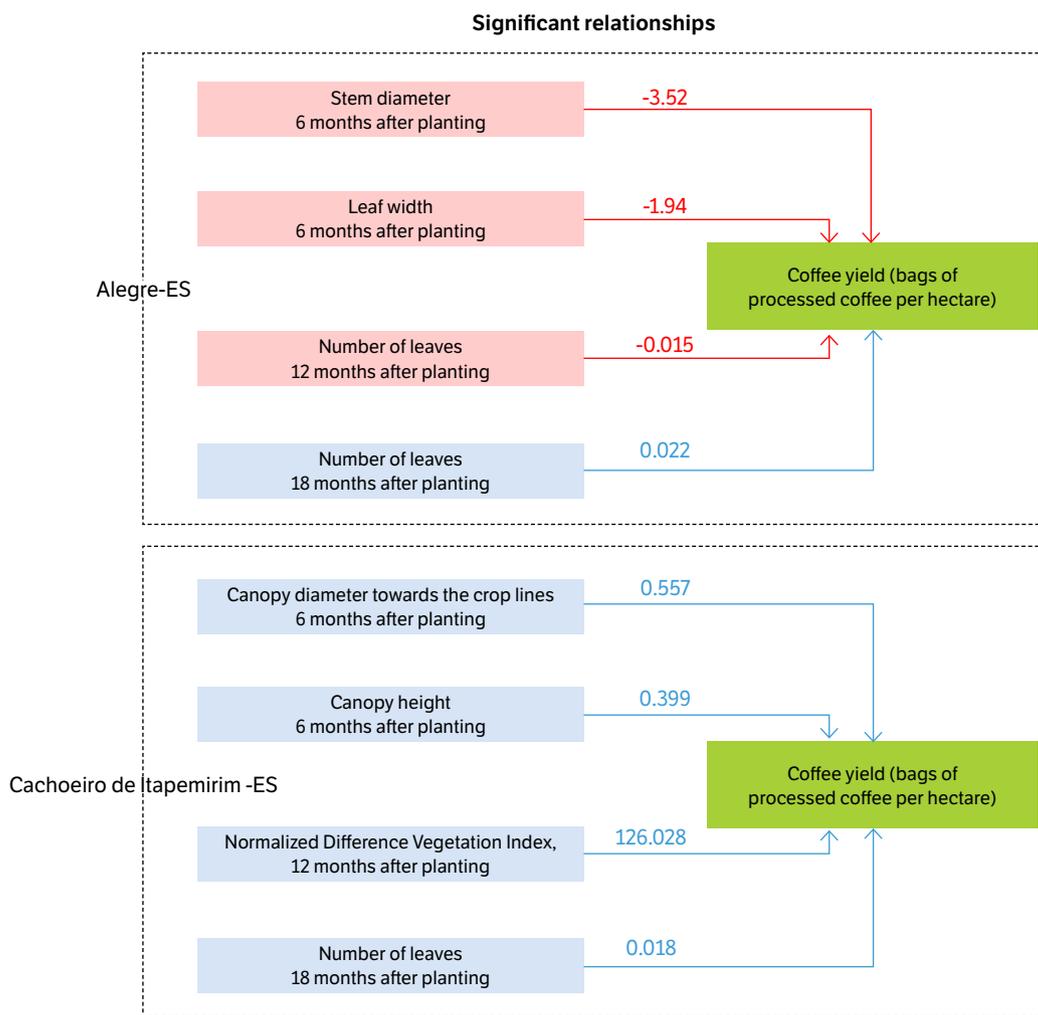


Figure 1. Diagram of the significant associations of morphophysiological traits with crop yield of 112 genotypes of *Coffea canephora* cultivated in two environments: Alegre (Espírito Santo, Brazil, 700 m altitude) and Cachoeiro de Itapemirim (Espírito Santo, Brazil, 140 m altitude).

DISCUSSION

The values of the coefficients of variation and selective accuracy indicate that the experiment was conducted with adequate control of sources of residual variation (Table 3). Values of the relative coefficient of variation greater than 1 suggest that

the experiment was conducted with high precision (Resende and Alves 2020), as the variance of genetic origin was greater than that of residual factors. In a study involving populations with distinct genetic bases, accuracy values of 67, 59, and 55% were estimated for the botanical groups Conilon, Robusta, and their hybrids, respectively (Alkimim et al. 2021). In a competition trial of Conilon coffee clones in agroforestry systems, a selective accuracy value of 87.13% was recorded (Senra et al. 2025a). Similarly, in an evaluation using augmented block design with a population of Conilon coffee of seminal origin, an accuracy of 53.88% was estimated (Senra et al. 2025b). The present experiment obtained a value of 78.51% (Table 3), which is classified as high accuracy (Resende and Alves 2020). Therefore, the genetic values are considered reliable for determining the best-performing genotypes in each environment and in the joint analysis.

The minimum selective accuracy required for the selection process in breeding programs is 70%, while a threshold of 90% is necessary to determine the value of cultivation and use (Resende and Alves 2020). Therefore, at this stage of the breeding program, it is possible to identify the highest-yielding genotypes. Considering the effect of both environments, the most productive genotypes were T3, 28, 69, 100, and 107, with genotypic values for crop yield ranging from 74.38 to 68.79 bags·ha⁻¹. In the municipality of Alegre, the top-performing genotypes were 28, T3, 69, 107, and 106, with yields between 72.84 to 64.50 bags·ha⁻¹, while in Cachoeiro de Itapemirim, T3, 28, 69, 100, and 107 exhibited yields between 80.43 to 74.26 bags·ha⁻¹.

The estimated heritability (h^2) was 28.02%, classified as moderate (Resende and Alves 2020), a value comparable to estimates obtained in the evaluation of seminal-source materials using the same statistical approach (Senra et al. 2025b). This value exceeds the estimates reported by Alkimim et al. (2021), which ranged from 6 to 10%, yet remains below that obtained by Senra et al. (2025a), which was 36.48%. The discrepancies in h^2 values can be attributed to differences in estimation methods, the genetic composition of studied populations, the number of evaluated genetic materials, and the statistical model used to determine genetic values.

The LRT analysis estimated statistical significance at 0.01% level for the genetic effect (Table 4). Other studies have also reported significant associations for the productivity trait, including research conducted by Ramalho et al. (2016), Mistro et al. (2019), Alkimim et al. (2021), and Senra et al. (2025a, 2025b). The r_1^2 was high, while the σ_{int}^2 was of low magnitude, demonstrating the potential to select high-productivity genotypes across both locations. This result may indicate a simple genotype-environment interaction, but further evaluation, including data from additional harvests and environments, is needed to confirm this conclusion. However, upon analyzing the components h^2 , r_1^2 , and σ_{int}^2 , alongside the statistical significance (0.01%) of the genetic effect and the absence of significance of the genotype-environment interaction, any doubts regarding the superiority of genotypes T3, 28, 69, 100, and 107 for cultivation in the evaluated locations can be dismissed.

Another study, which used the same traits, identified high correlation values with strong statistical significance between the studied traits (Senra et al. 2023). Parameters that define the growth and development of Conilon coffee trees often exhibit a strong genetic correlation, as reported by Covre et al. (2016), studying the development of Conilon coffee seedlings, and by Carvalho et al. (2010), analyzing the correlation between productivity and morphological traits in Arabica coffee tree. Carvalho et al. (2010) estimated significant and positive genotypic correlations between productivity, stem diameter, and the number of plagiotropic branches in Arabica coffee trees. Certain evaluated traits, such as NDVI and SPAD, demonstrated genetic correlations with plant vigor (Silva et al. 2022). Vegetative vigor, in turn, should be considered a reliable criterion for selecting superior coffee genotypes. A high correlation between vegetative vigor and productivity was observed for Arabica coffee (Severino et al. 2002). For Conilon coffee, vegetative vigor serves as a key criterion in selecting the best genotypes for cloning (Moura et al. 2022), in defining breeding strategies for the species (Alkimim et al. 2021), and in predicting genetic gains (Carias et al. 2016). Therefore, given the theoretical framework and the extensive number of evaluated traits, high VIF values would be expected.

For an accurate path analysis, it is necessary to identify and address multicollinearity in the correlation matrix among explanatory variables (Borges et al. 2011). When multicollinearity is present, the associated variances of the path coefficient estimators can increase drastically, leading to unreliable estimates that lack biological coherence (Bizeti et al. 2004, Coimbra et al. 2005, Toebe and Cargnelutti Filho 2013). By identifying sources of collinearity, 16 variables were eliminated in the municipality of Alegre (Table 7) and 17 in Cachoeiro de Itapemirim (Table 8). Although ridge regression analysis could be applied to path analysis in the presence of multicollinearity, discarding variables with high VIF values was the most conservative strategy, helping prevent overparameterization of the model and the estimation of artificially high values lacking

biological significance. Path analysis was performed using traits with VIF values below 10 (Tables 7 and 8), ensuring the identification of traits with a significant effect and biological coherence in relation to the productivity of Conilon coffee across both environments.

For both municipalities, only four traits exhibited a significant association with the productivity (Table 9 and Fig. 1). Importantly, these parameters require simple evaluations, offering advantages in terms of time efficiency and cost reduction for *C. canephora* breeding programs. In Alegre, stem diameter and leaf width at six months post-planting, as well as leaf count at 12 months post-planting, demonstrated a negative correlation. These values may reflect environmental influences on growth conditions. Observations indicate that coffee trees cultivated in higher-altitude environments (700 m) tended to exhibit a larger stem base diameter, fewer leaves, and larger leaf size compared to trees grown at lower altitudes (140 m) (Senra et al. 2023). Therefore, in higher-altitude locations, evaluations for indirect and early selection of more productive genotypes should be delayed for more than a year. In the municipality of Cachoeiro de Itapemirim, early indirect selection could be performed at three distinct intervals: six months post-planting by measuring canopy diameter and height, 12 months post-planting through NDVI readings, and 18 months post-planting by counting the number of leaves.

Analyzing the development of coffee trees is essential for establishing effective crop management practices and selecting suitable cultivars (Freitas et al. 2007, Carvalho et al. 2010). Taller coffee trees tend to produce a greater number of plagiotropic branches, while canopies with a larger diameter generally develop a higher number of fruiting buds per branch (Freitas et al. 2007). In a study involving Arabica coffee cultivars, positive phenotypic correlations were observed between plant height, stem diameter, canopy diameter, and overall productivity (Alves et al. 2021). Leaf NDVI readings provide insights into the physiological state of coffee plants and assist in identifying genotypes with lesser vegetative stress (Silva et al. 2022). NDVI values close to unity suggest a higher concentration of chlorophyll and greater vegetative vigor, which consequently correlates with higher productive potential (Galvanin et al. 2014, Rissini et al. 2015). By combining NDVI values with leaf count data, it is possible to infer the efficiency of the photosynthetic apparatus and to predict the productive potential of coffee plants.

CONCLUSION

The best five genotypes for both locations were T3, 28, 69, 100, and 107. In Alegre (700 m a.s.l.), the best performers were 28, T3, 69, 107, and 106, while in Cachoeiro de Itapemirim they were T3, 28, 69, 100, and 107. Deviance analysis showed a significant genetic effect, whereas the genotype \times location interaction was non significant. Combined with the low interaction variance and high correlation of genotype performance across sites, this suggests a simple genotype-environment interaction. Further studies across more environments and higher altitudes are needed to confirm this.

Multicollinearity analysis removed traits that inflated the model, retaining only variables with a VIF below 10. This approach prevented overparameterization and reduced errors due to collinearity. For early selection of high-performing Conilon coffee genotypes, breeding programs should prioritize evaluating leaf number, NDVI, and canopy diameter and height.

CONFLICT OF INTEREST

Nothing to declare.

AUTHORS' CONTRIBUTION

Conceptualization: Senra, J. F. B.; **Methodology:** Senra, J. F. B., Ferreira, A. and Milheiros, I. S.; **Formal analysis:** Senra, J. F. B.; **Investigation:** Senra, J. F. B., Esposti, M. D. D., Milheiros, I. S., Silva, T. S. and Ramos, I. B.; **Data curation:** Senra, J. F. B. and Rodrigues, W. N.; **Writing—original draft:** Senra, J. F. B., Silva, T. S. and Ramos, I. B.; **Writing—review & editing:** Rodrigues, W. N. and Colodetti, T. V.; **Visualization:** Senra, J. F. B., Rodrigues, W. N. and Colodetti, T. V.; **Supervision:**

Senra, J. F. B. and Ferreira, A.; **Project administration:** Senra, J. F. B. and Esposti, M. D. D.; **Validation:** Senra, J. F. B. and Ferreira, A. **Resources:** Senra, J. F. B.; **Final approval:** Rodrigues, W. N.

DATA AVAILABILITY STATEMENT

The data supporting the findings of this study are available as a supplementary file accompanying this manuscript. Supplementary Material at: <https://doi.org/10.5281/zenodo.18564551>

FUNDING

Fundação de Amparo à Pesquisa do Espírito Santo 
Grant No.: 1,118/2024

DECLARATION OF USE OF ARTIFICIAL INTELLIGENCE TOOLS

The authors declare that no generative artificial intelligence tools were used in the preparation of this manuscript.

ACKNOWLEDGMENTS

The authors would like to thank the Coffee Research Consortium, and the Espírito Santo State Secretariat of Agriculture, Supply, Aquaculture, and Fisheries for their support.

REFERENCES

- Alkimim, E. R., Caixeta, E. T., Sousa, T. V., Gois, I. B., Lopes da Silva, F., Sakiyama, N. S., Zambolim, L., Alves, R. S. and Resende, M. D. V. (2021). Designing the best breeding strategy for *Coffea canephora*: genetic evaluation of pure and hybrid individuals aiming to select for productivity and disease resistance traits. *PLoS One*, 16, e0260997. <https://doi.org/10.1371/journal.pone.0260997>
- Alves, G. S. P., Coelho, A. P. and Lemos, L. B. (2021). Crescimento vegetativo, produtividade e qualidade pós-colheita de cultivares de café de porte baixo em região de baixa altitude. *Agroecossistemas*, 13, 63-83. <https://doi.org/10.18542/ragros.v13i1.8253>
- Azevedo, A. M., Seus, R., Gomes, C. L., Freitas, E. M., Candido, D. M., Silva, D. J. H. and Carneiro, P. C. S. (2016). Correlações genotípicas e análise de trilha em famílias de meios-irmãos de couve de folhas. *Pesquisa Agropecuária Brasileira*, 51, 35-44. <https://doi.org/10.1590/S0100-204X2016000100005>
- Bizeti, H. S., Carvalho, C. G. P., Souza, J. R. P. and Destro, D. (2004). Path analysis under multicollinearity in soybean. *Brazilian Archives of Biology and Technology*, 47, 669-676. <https://doi.org/10.1590/S1516-89132004000500001>
- Borges, V., Souza Sobrinho, F., Lêdo, F. J. S. and Kopp, M. M. (2011). Associação entre caracteres e análise de trilha na seleção de progênies de meios-irmãos de *Brachiaria ruziziensis*. *Revista Ceres*, 58, 765-772. <https://doi.org/10.1590/S0034-737X2011000600013>
- Carias, C. M. O. M., Gravina, G. A., Ferrão, M. A. G., Fonseca, A. F. A., Ferrão, R. G., Vivas, M. and Viana, A. P. (2016). Predição de ganhos genéticos via modelos mistos em progênies de café Conilon. *Coffee Science*, 11, 39-45. <https://coffeescience.ufpa.br/index.php/Coffeescience/article/view/961>



- Carvalho, A. M., Botelho, C. E., Ferreira, A. D., Teramoto, E. T., Lima, A. E., Miyazaki Junior, F. S. and Guerreiro Filho, O. (2022). Initial vegetative and reproductive development of coffee cultivars in Vale do Ribeira Paulista. *Semina: Ciências Agrárias*, 43, 961-972. <https://doi.org/10.5433/1679-0359.2022v43n3p961>
- Carvalho, A. M., Mendes, A. N. G., Carvalho, G. R., Botelho, C. E., Gonçalves, F. M. A. and Ferreira, A. D. (2010). Correlação entre crescimento e produtividade de cultivares de café em diferentes regiões de Minas Gerais, Brasil. *Pesquisa Agropecuária Brasileira*, 45, 269-275. <https://doi.org/10.1590/S0100-204X2010000300006>
- Coimbra, J. L. M., Benin, G., Vieira, E. A., Oliveira, A. C., Carvalho, F. I. F., Guidolin, A. F. and Soares, A. P. (2005). Consequências da multicolinearidade sobre a análise de trilha em canola. *Ciência Rural*, 35, 347-352. <https://doi.org/10.1590/S0103-84782005000200015>
- [CONAB] Companhia Nacional de Abastecimento (2022). Acompanhamento da safra brasileira de café – safra 2022. Brasília: CONAB. Available at: https://www.icafe.cr/wp-content/uploads/informacion_mercado/reportes_mercado/entidades_cafetaleras/Estimado%20de%20Cosecha%20de%20Brasil.pdf. Accessed on: June 26, 2025.
- Covre, A. M., Canal, L., Partelli, F. L., Alexandre, R. S., Ferreira, A. and Vieira, H. D. (2016). Development of clonal seedlings of promising Conilon coffee (*Coffea canephora*) genotypes. *Australian Journal of Crop Science*, 10, 385-392. <https://doi.org/10.21475/ajcs.2016.10.03.p7235>
- Cruz, C. D. (2016). Genes software: extended and integrated with the R, Matlab and Selegen. *Acta Scientiarum*, 38, 547-552. <https://doi.org/10.4025/actasciagron.v38i3.32629>
- Davis, A. P. and Rakotonasolo, F. (2021). Six new species of *Coffea* from northern Madagascar. *Kew Bulletin*, 76, 497-511. <https://doi.org/10.1007/s12225-021-09952-5>
- Espindula, M. C., Dalazen, J. R., Rocha, R. B., Teixeira, A. L., Diocleciano, J. M., Dias, J. R. M., Schmidt, R., Lima, P. P., Lima, G. M. and Gama, W. (2022). Robustas amazônicas: os cafeeiros cultivados em Rondônia. Brasília: Embrapa. <https://www.alice.cnptia.embrapa.br/alice/handle/doc/1152388>
- Favarin, J. L., Dourado Neto, D., García, A. G., Villa Nova, N. A. and Favarin, M. G. G. V. (2002). Equations for estimating the coffee leaf area index. *Pesquisa Agropecuária Brasileira*, 37, 769-773. <https://doi.org/10.1590/S0100-204X2002000600005>
- Ferrão, M. A. G., Mendonça, R. F., Fonseca, A. F. A., Ferrão, R. G., Senra, J. F. B., Volpi, P. S., Verdin Filho, A. C. and Comério, M. (2021). Characterization and genetic diversity of *Coffea canephora* accessions in a germplasm bank in Espírito Santo, Brazil. *Crop Breeding and Applied Biotechnology*, 21, e36132123. <https://doi.org/10.1590/1984-70332021v21n2a32>
- Ferrão, R. G., Fonseca, A. F. A., Ferrão, M. A. G. and De Muner, L. H. (2019). Conilon coffee. 3. ed. Vitória: Incaper.
- Filla, V. A., Coelho, A. P., Grossi Terceiro, M., Morello, O. F. and Lemos, L. B. (2023). Initial vegetative development and early selection of arabica coffee cultivars in a low-altitude region. *Bragantia*, 82, e20230098. <https://doi.org/10.1590/1678-4499.20230098>
- Freitas, Z. M. T. S., Oliveira, F. J., Carvalho, S. P., Santos, V. F. and Santos, J. P. (2007). Avaliação de caracteres quantitativos relacionados com o crescimento vegetativo entre cultivares de café arábica de porte baixo. *Bragantia*, 66, 267-275. <https://doi.org/10.1590/S0006-87052007000200010>
- Galvanin, E. A. S., Neves, S. M. A. S., Cruz, C. B. M., Neves, R. J., Jesus, P. H. H. and Kreitlow, J. P. (2014). Avaliação dos índices de vegetação NDVI, SR e TVI na discriminação de fitofisionomias dos ambientes do Pantanal de Cáceres/MT. *Ciência Florestal*, 24, 707-715. <https://doi.org/10.5902/1980509815729>
- Mistro, J. C., Resende, M. D. V., Fazuoli, L. C. and Vencovsky, R. (2019). Effective population size and genetic gain expected in a population of *Coffea canephora*. *Crop Breeding and Applied Biotechnology*, 19, 1-7. <https://doi.org/10.1590/1984-70332019v19n1a01>
- Moura, W. M., Pedrosa, A. W., Oliveira, R. L., Cecon, P. R., Ferrão, R. G., Ferrão, M. A. G. and Verdin Filho, A. C. (2022). Selection of Conilon coffee clones for the Zona da Mata region of Minas Gerais, Brazil. *Coffee Science*, 17, e171995. <https://doi.org/10.25186/v17i.1995>

- R Core Team (2022). R: A language and environment for statistical computing. Vienna: R Foundation for Statistical Computing. Available at: <https://www.R-project.org/>. Accessed on: June 26, 2025.
- Ramalho, A. R., Rocha, R. B., Souza, F. F., Veneziano, W. and Teixeira, A. L. (2016). Progresso genético da produtividade de café beneficiado com a seleção de clones de cafeeiro Conilon. *Revista Ciência Agronômica*, 47, 516-523. <https://www.scielo.br/j/rca/a/sVWzTtsZ5JDt9zNWKtnbqyH>
- Resende, M. D. V. (2007). Software SELEGEN-REML/BLUP: Statistical System and Computerized Genetic Selection Via Mixed Linear Models. Colombo: Embrapa Florestas.
- Resende, M. D. V. (2016). Software Selegen-REML/BLUP: a useful tool for plant breeding. *Crop Breeding and Applied Biotechnology*, 16, 330-339. <https://doi.org/10.1590/1984-70332016v16n4a49>
- Resende, M. D. V. and Alves, R. S. (2020). Linear, generalized, hierarchical, Bayesian and random regression mixed models in genetics/genomics in plant breeding. *Functional Plant Breeding Journal*, 3, 121-152. <https://doi.org/10.35418/2526-4117/v2n2a1>
- Rissini, A. L. L., Kawakami, J. and Genú, A. M. (2015). Índice de vegetação por diferença normalizada e produtividade de cultivares de trigo submetidas a doses de nitrogênio. *Revista Brasileira de Ciência do Solo*, 39, 1703-1713. <https://doi.org/10.1590/01000683rbc20140686>
- Rocha, R. B., Teixeira, A. L., Ramalho, A. R., Espindula, M. C., Lunz, A. M. P. and Souza, F. F. (2021). *Coffea canephora* breeding: estimated and achieved gains from selection in the Western Amazon, Brazil. *Ciência Rural*, 51, e20200713. <https://doi.org/10.1590/0103-8478cr20200713>
- Romano, L. S., Giomo, G. S., Coelho, A. P., Filla, V. A. and Lemos, L. B. (2022). Characterization of Yellow Bourbon coffee strains for the production of differentiated specialty coffees. *Bragantia*, 81, e2222. <https://doi.org/10.1590/1678-4499.20210236>
- Schmidt, E. R., Amaral, J. A. T., Santos, J. S. and Schmidt, O. (2015). Allometric model for estimating leaf area in clonal varieties of coffee (*Coffea canephora*). *Revista Ciência Agronômica*, 46, 740-748. <https://www.scielo.br/j/rca/a/B4WNDkZsZMVdtb3L4DF8vCw>
- Senra, J. F. B., Comerio, M., Oliveira, R. G., Silva, V. A. C., Gomes, W. M., Ferrão, M. A. G., Verdin Filho, A. C., Volpi, P. S., Ferrão, R. G., Fonseca, A. F. A. and Tomaz, M. A. (2025a). Evaluation of the genetic potential of coffee trees in agroforestry systems with rubber trees. *Bragantia*, 84, e20240182. <https://doi.org/10.1590/1678-4499.20240182>
- Senra, J. F. B., Silva, J. A., Ferreira, A., Esposti, M. D. D., Ferrão, M. A. G., Fassarella, K. M., Silva, U. R., Milheiros, I. S. and Silva, F. G. (2023). Initial performance and genetic diversity of coffee trees cultivated under contrasting altitude conditions. *Scientia Agricola*, 80, e20220163. <https://doi.org/10.1590/1678-992X-2022-0163>
- Senra, J. F. B., Silva, V. A. C., Esposti, M. D. D., Ferreira, A., Milheiros, I. S., Ramos, I. B., Oliveira, R. G. and Benevenuto, L. M. (2025b). Selection of differentiated maturity genotypes of *Coffea canephora*. *Acta Scientiarum Agronomy*, 47, e70812. <https://doi.org/10.4025/actasciagron.v47i1.70812>
- Severino, L. S., Sakiyama, N. S., Pereira, A. A., Miranda, G. V., Zambolim, L. and Barros, U. V. (2002). Associações da produtividade com outras características agronômicas de café (*Coffea arabica* L. "Catimor"). *Acta Scientiarum Agronomy*, 24, 1467-1471. <https://doi.org/10.4025/actasciagron.v24i0.2405>
- Silva, J. A., Senra, J. F. B., Esposti, M. D. D., Milheiros, I. S., Silva, U. R., Conceição, A. O. and Zacarias, A. J. (2022). Characterization of the vegetative vigor, and SPAD readings and vegetation index in a *Coffea canephora* population. *Research Society and Development*, 11, e254111537314. <https://doi.org/10.33448/rsd-v11i15.37314>
- Souza, C. A., Rocha, R. B., Santos, M. R. A., Lopes, T. A., Teixeira, A. L. and Espindula, M. C. (2021). *In vitro* pollination and fluorescence microscopy for characterization of gametophytic self-incompatibility of *Coffea canephora* Pierre Ex A. Froehner. *Crop Breeding and Applied Biotechnology*, 21, e37692142. <https://doi.org/10.1590/1984-70332021v21n4a51>

Souza, E. M. R., Senra, J. F. B. and Silva, J. A. (2025). Cultivares de cafeeiros indicados para o estado do Espírito Santo. In J. F. B. Senra, M. A. P. Guimarães, M. A. G. Ferrão, L. C. S. Caetano, J. A. Silva, T. S. Souza and F. T. Alixandre (Eds.). Tópicos especiais na produção de cafés de qualidade (p. 17-67). Vitória: Incaper. <https://doi.org/10.54682/livro.9788589274517>

Spinelli, V. M., Moraes, M. S., Alves, D. S. B., Rocha, R. B., Ramalho, A. R. and Teixeira, A. L. (2018). Contribution of agronomic traits to the *Coffea canephora* Pierre ex A. Froehner in the western Amazon region. *Coffee Science*, 13, 333-340. <https://doi.org/10.25186/cs.v13i3.1452>

Teixeira, D. H. L., Oliveira, M. S. P., Gonçalves, F. M. A. and Nunes, J. A. R. (2012). Correlações genéticas e análise de trilha para componentes da produção de frutos de açaizeiro. *Revista Brasileira de Fruticultura*, 34, 1135-1142. <https://doi.org/10.1590/S0100-29452012000400022>

Toebe, M. and Cargnelutti Filho, A. (2013). Não normalidade multivariada e multicolinearidade na análise de trilha em milho. *Pesquisa Agropecuária Brasileira*, 48, 466-477. <https://doi.org/10.1590/S0100-204X2013000500002>

Tolera, B., Gedebo, A. and Tena, E. (2024). Genetic variability, character association and path analysis in sugarcane genotypes. *Archives of Agronomy and Soil Science*, 70, 1-15. <https://doi.org/10.1080/03650340.2024.2331036>