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Core ideas

Ten agro-morphological groups of the *Coffea arabica* germplasm collection from INIA, Peru were characterized.

Phytosanitary characterization shows promising coffee genotypes against coffee leaf rust.

Promising genotypes from INIA´s germplasm collection would be useful for coffee breeding programs.

Agro-morphological characterization and diversity analysis of C*offea arabica* germplasm collection from INIA, Peru.

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Abbreviations: INIA-CGC, INIA´s coffee germplasm collection; ANOVA, analysis of variance; GCV, genotypic coefficient of variation; PCV, phenotypic coefficient of variation;

ECV, environmental coefficient of variation; H, heritability; VI, variation index; CA, cluster analysis; PCA, principal component analysis.

ABSTRACT

Coffee (*Coffea arabica* L.) plays a major role in the economy of Peru and the world. The present study aims to elucidate the agro-morphological variability of coffee genotypes maintained in the INIA´s germplasm collection. Therefore, 20 vegetative, reproductive, and phytosanitary traits of 162 coffee accessions of INIA's germplasm collection were evaluated and analyzed. Correlation results indicate that a simultaneous selection of characters, such as number of branches per plant, number of nodes per branch, leaf area and weight of a hundred fruits, can contribute to increase coffee yields. Additionally, coffee yield was negatively correlated with the incidence and severity of coffee leaf rust, and interestingly the occurrence of small and compact coffee plants with high resistance to the disease was also found. The analysis of Tocher and Mahalanobis D^2 determined the formation of 10 groups of divergent coffee accessions; where clusters 1 (accession codes 20, 29, 38, 54, 67, 71, 117, 24, 26 and 27), 5 (accession codes 46 and 53), 9 (accession code 159), and 10 (accession code 203) group promising accessions that can be used in breeding programs. Principal component analysis (PCA) showed that at least five of its principal components managed to explain 70.01% of the total variation in the collection. Finally, the high coefficients obtained for the phenotypic, genotypic and heritability variation confirm the existence of additive genes in the evaluated population, that would ensure the success of coffee breeding programs based on the selection of traits of agronomic importance.

1. INTRODUCTION

Coffee is the main agricultural export product in Peru, and it has a great impact on the economy of rural families. In 2020, more than 227,640 tons of coffee were produced, and currently Peru places eighth in the ranking of exporting countries (ICO, 2021a; ICO, 2021b). Coffee belongs to the family *Rubiaceae* and to the genus Coffea, which has many species; being the most commercialized in the world *Coffea arabica* and *Coffea canephora* (Farah & Ferreira dos Santos, 2015). In Peru, Arabic cultivars predominate, mainly with the varieties Typica, Caturra, Catimor, Pache and Bourbon (INIA, 2019).

Germplasm banks under ex situ conditions make possible to preserve and maintain genetic variability in a long term. Characterization and analysis of their diversity are important because they can provide valuable and useful information for the management and use of genetic resources for crop improvement (Aghaee et al., 2010; Ivoglo et al., 2008). Characterization to determine the variability of germplasm banks has been widely approached using agro-morphological characteristics (Kumari et al., 2016) due to its low cost and not being very complex (Parsaeian et al., 2011). According to Atinafu and Mohammed (2017b), the collection of agro-morphological data could provide sufficient information for the efficient characterization of coffee variability; knowledge that could lead to a better exploitation of germplasm through the appropriate selection of genotypes that contain traits of agronomic interest such as productive stability, resistance to pests and diseases, grains of larger size and organoleptic quality, or identifying short-sized genotypes with tolerance to stress of challenging climates and soils (Giles et al., 2018; Texeira et al., 2013). Therefore, the main goal of plant breeding is to establish a hybridization program followed by the selection of offspring (Giles et al., 2018; Sanwal et al., 2015).

For the success of a breeding program, a series of basic information must be made available regarding the genetic structure of the species, the magnitude of the variability present in the population, and the heritability in a broad sense for the different morphological characters of the genotypes that will be improved (Alemayehu, 2019; da Silva et al., 2015; Ferrão et al., 2008). Consequently, estimating the coefficients of phenotypic, genotypic, and environmental variation are useful to quantify the existing richness within a germplasm collection (Cheserek et al., 2020; Weldemichel et a., 2017). However, the use of heritability provides the breeder with better information on the phenotypic stability of the individual, since it is based on characters that can be transmitted from one generation to another (Paw et al., 2020; Alemayehu, 2019); that is, the breeder can select one or several accessions based on their phenotypic behavior (Weldemichael et al., 2017). On the other hand, the correlation coefficient allows directing breeding strategies, based on the effects of association between two or more characters (Atinafu et al., 2017; Kifle et al., 2018). Generally, plant breeding programs seek to implement criteria based on the selection of traits of agronomic interest, especially those related to high yield and its components (Atinafu & Mohammed, 2017a; Merga et al., 2019; Paw et al., 2020; WeldeMichael, 2019).

Likewise, many plant breeders have used multivariate analysis techniques to study genetic divergence, through the analysis of data obtained from the characterization of germplasm collections, in order to define the main breeding strategies to achieve higher genetic gains but maintaining an adequate genetic base in the population (Aghaee et al., 2010; da Silva et al., 2015; Ferrão et al., 2008; Ivoglo et al., 2008). Multivariate analysis using some classic methods allows calculating the dissimilarity between genotypes; cluster analysis (CA) and principal component analysis (PCA) are frequently used to classify and group different genotypes by the mean value of the characters evaluated. In addition, multivariate analysis allows predicting and explaining complex data, reducing the dimension of use

multiple dependent variables that are generally correlated (Cruz, 2013; Dubberstein et al., 2020; Niazian & Niedbała, 2020; Sanwal et al., 2015; Teixeira et al., 2013). For example, in Egypt, Atinafu and Mohammed (2017b) evaluated the morphological differences between 124 accessions, using 26 quantitative traits through clustering. In a similar study, WeldeMichael et al. (2013) studied the genetic variability of 49 accessions using analysis of variance, clustering and principal components. In Saudi Arabia, Tounekti et al. (2017) evaluated the genetic diversity of 19 accessions using clustering and principal component analysis techniques. In Brazil, Covre et al. (2016) studied the genetic divergence of 33 genotypes using phenotypic correlations and cluster analysis. Likewise, da Silva et al. (2015), Giles et al. (2018), Fonseca et al. (2006), Ivoglo et al. (2008), and Teixeira et al. (2013) also studied the genetic diversity of coffee germplasm using correlation coefficients, cluster analysis, and principal component analysis.

Pichanaki Agrarian Experimental Station of the National Institute of Agrarian Innovation (INIA) preserves an important germplasm collection of 169 accessions of coffee from six Peruvian regions. However, the information on the agro-morphological characterization of this coffee collection is still limited. Thus, the evaluation and diversity analysis of vegetative, reproductive, and phytosanitary characters are the main purposes of this study.

2. MATERIALS AND METHODS

2.1 Plant Material

INIA's Coffee Germplasm Collection (INIA-CGC) was established in 2015 with the support of KOPIA (Korea Program on International Agriculture), to provide valuable information for its diversity genetic conservation and breeding programs. Under an agroforestry system that include fruit and wood trees, INIA-CGC maintains a total of 169

accessions of coffee plants from Amazonas, Cajamarca, Huánuco, Junín, Pasco, and Ucayali, the main growing regions in Peru. Each accession is composed by 10 plants separated 2.5 x 1.0 m between them. Variety denominations available for the coffee accessions were provided by the local growers (Table S1).

2.2 Location

INIA-CGC is located at Pichanaki Agrarian Experimental Station, in the province of Chanchamayo, Junín region, with coordinates 10°55'29"S and 74°52'36"W, at 774 masl. Average temperature of 26.70° C (maximum 32.62° C; minimum 20.74° C), relative humidity of 78% and precipitation of 1589.60 mm (Figure S1). High hill physiography, soil presents silty clay loam texture, pH of 4.49, effective cation exchange capacity (ECEC) of 5.11 meq/100g and aluminum saturation with respect to the CEC of 15.67%. Agronomic management practices were carried out based on the technological package proposed by the INIA National Coffee Program, which consisted of applying to the plants 250 ml of Tenaz® fungicide plus 1 L of trihormonal foliar (auxins, gibberellins and cytokinins) diluted in 200 L of water, before flowering begins of each campaign (June and July), in order to promote rapid recovery of the plants. Likewise, 461 g/plant of the fertilizer YaraMila Tristar™ (15-15-15) plus 2 kg/plant of organic matter (Sungro Horticulture) was divided and applied in three doses, in the phenological phases of grain filling, harvest and flowering of the crop.

2.3 Variables assessed

Agro-morphological characters were evaluated in 162 accessions of the INIA-CGC, each with 5 plants, when the accessions reached 6 years of vegetative development (supplementary material). Seven coffee accessions of the germplasm collection, due to adverse conditions, have less than 5 plants, for this reason they were not included in the present study. Nineteen

quantitative characters and one qualitative character were evaluated, divided into 10 agronomic and 10 morphological descriptors, which are defined as follow: plant height (PH) measured from the ground level to the apical bud of the plant; trunk diameter (TD) measured at 5 cm from soil level; number of branches per plant (NBP); number of fruit-bearing branches (NFB); length of fruit-bearing branches (LFB) of the middle third of the plant; number of nodes per branch (NNB), measured from four fruit-bearing branches; length of internodes (LIN) obtained from the LFB divided with the NNB; orthotropic internode length (OIL), obtained from the division of the PH and the number of orthotropic nodes; degree of plant inclination (DPI) according to an arbitrary scale where 1 = vertical trunk, 2 = trunk with slight inclination (< 20°), 3 = moderately inclined trunk (20° to 45°), 4 = trunk very steep (> 45°); leaf area (LA) from leaves of the fourth node of a branch located in the middle third of the plant, obtained by the product of the length (L) and width (W) of the leaf multiplied by the constant 0.68 (L x W x 0.68) (Adem, 2020); fruit geometric diameter (FGD) and seed geometric diameter (SGD), determined as the cube root of the average diameter of the length, width and thickness of 10 fruits and grains per repetition of each accession; weight of a hundred fruits (WHF); fruit production per plant (FPP), corresponding to the cumulative harvest of the first 5 seasons (2017–2021); percentage of vain fruits (PVF), calculated by the number of floating fruits from a sample of 100 physiologically mature and apparently healthy fruits (Adem et al., 2020; Atinafu et al., 2017; Beksisa et al., 2017; International Plant Genetic Resources Institute, 1996; Ivoglo et al., 2008; Merga et al, 2019; Olika et al., 2011; Tounekti et al., 2017; WeldeMichael et al., 2013). Likewise, the damage caused by the presence of the coffee berry borer (*Hypothenemus hampei*) was recorded, expressed as the percentage of infestation evaluated in 300 fruits per plant (PFB). The incidence (LRI) and severity (LRS) of coffee leaf rust caused by *Hemileia vastatrix* were evaluated on 10 pairs of leaves from the branches of the lower, middle and upper strata of each plant. The evaluations

were carried out every 30 days for 18 months, between 2020 and 2021. The LRS was estimated according to the scale proposed by Sera et al. (2007), where: 0 = healthy leaves, 1 = leaves with 1 to 5 chlorotic lesions and percentage of branch damage varies from 1 to 9%; 2 = leaves with 1 to 5 lesions with sporulation, with the presence of branch damage between 1 to 9%; 3 = leaves with 6 to 25 sporulating lesions with 10 to 35% branch damage; 4 = Leaves with more than 25 sporulating lesions and branch damage above 35%. The accessions that presented severity indexes between 0 and 1 were considered resistant, 2, 3 and 4 were designated as susceptible. Damage caused by coffee leafminer (*Leucoptera caffeella*) was evaluated as the arc sine of the percentage of infested leaves (LMI) of a branch located in the middle stratum of the plant. Percentage of plant defoliation (PPD) was determined based on the methodology proposed by Alvarado-Alvarado and Solórzano-Buitrago (2001), which consisted of obtaining the percentage of fallen leaves for each accession, from the result of the difference in potential of leaves and the number of leaves present on the branches at the time of each evaluation, for this measure the marked branches were used to evaluate coffee leaf rust. For the cases of PFB, LRI and LMI, the data were transformed to the arc sine of the percentage of damage caused by the pest (arsen$\sqrt{X}$).

2.4 Statistical analysis

Data analyzes were carried out for the 20 characters evaluated. An analysis of variance (ANOVA) was performed to verify significant differences between the variables according to a completely randomized design (CRD). Subsequently, the descriptive statistics (average, standard deviation, minimum, maximum) and genetic parameters were calculated to determine the agro-morphological variability present in the germplasm collection. Genotypic, phenotypic, and environmental coefficients of variation (GCV, PCV, ECV), variation index

(IV) and heritability (H) were estimated based on the formulas suggested by Falconer and Mackay (2009) and Singh (1981):

Genotypic coefficient of variation $(\text{GCV}) = \frac{100\sqrt{\hat{\phi}_g}}{\hat{\mu}}$; Phenotypic coefficient of variation $(\text{PCV}) = \frac{100\sqrt{\text{QMG}}}{\hat{\mu}}$; Environment coefficient of variation $(\text{ECV}) = \frac{100\sqrt{\text{QMR}}}{\hat{\mu}}$; Variation index $(\text{VI}) = \frac{\text{GCV}}{\text{ECV}}$; and Heritability in broad sense $(H) = \frac{\sigma_g^2}{\sigma_p^2}$; where: Genotypic variability $\left(\hat{\phi}_g\right) = \frac{\text{QMG} - \text{QMR}}{r}$; QMG = mean square of the genotypic; QMR = Mean square of the residual; σ_g^2 = Genotypic variance; σ_p^2 = Phenotypic variance; $\hat{\mu}$ = Average of the agro-morphological characters; r = Number of repetitions.

To study the associations between the variables evaluated, the Pearson correlation coefficient (r) was used with a probability of 5% ($P \leq 0.05$). The phenotypic and genotypic correlations were determined based on the formulas proposed by Cruz (2013):

Phenotypic correlation coefficient $(rp) = \frac{\hat{\phi}p_{xy}}{\hat{\phi}p_x\hat{\phi}p_y}$; where: $\hat{\phi}p_{xy}$ = phenotypic covariance between characters x and y; $\hat{\phi}p_x$ = phenotypic variance of character x; $\hat{\phi}p_y$ = phenotypic variance of character y.

Genotypic correlation coefficient $(rg) = \frac{\hat{\phi}g_{xy}}{\hat{\phi}g_x\hat{\phi}g_y}$; where: $\hat{\phi}g_{xy}$ = genotypic covariance between characters x and y; $\hat{\phi}g_x$ = genotypic variance of character x; $\hat{\phi}g_y$ = genotypic variance of character y.

Genetic divergence was determined based on 19 quantitative characters, by estimating the generalized Mahalanobis distance, for which the following equation was used: $D^2 p = (X_i - X_j) S^{-1} (X_i - X_j)$; where D^2p= Total generalized distance between p characters; X_i and X_j = p averages for the vectors of genotypes i and j, respectively. S^{-1} = The inverse of the pooled covariance matrix (Cruz & Souza Carneiro, 2006; Mahalanobis, 1936). Then, the dissimilarity means were used to form groups using the Tocher Optimization method. To facilitate the analysis, only the groups with many accessions were sub-divided, following the previous procedure. Finally, a principal component analysis (PCA) was carried out in order to evaluate and identify the most diverse accessions, which gather useful characters for coffee breeding. In addition, with the estimation of the matrix of Eigen vectors, a two-dimensional graph was represented to explain the variability found. All these analyzes were developed with the Software GENES (Cruz, 2013).

3. RESULTS AND DISCUSSION

3.1 Analysis of Variance

ANOVA for each of the agro-morphological variables revealed highly significant differences ($P \leq 0.05$ and $P \leq 0.01$) among all the accessions studied (Table 1). These results support the hypothesis of the existence of great phenotypic variability in the INIA-CGC, especially for characters associated with coffee production and health. The variability observed in this study favors the effectiveness of the selection for genetic breeding of the characteristics of agronomic interest through hybridizations between genotypes of good performance in the field. Furthermore, Olika et al. (2011) and Hedrick (2009) mention that the prevalence of such variability in an autogamous species such as *Coffea arabica* is very

important and that can be attributed to evolutionary trends or natural mutations that occur within the population. In general, previous research has reported similar results to those observed in this work, determining high genetic diversity in coffee accessions through the study of quantitative and qualitative characters (Adem et al., 2020; Alemayehu, 2019; Atinafu & Mohammed, 2017b; Beksisa et al., 2021; Tounekti et al., 2017; WeldeMichael et al., 2013; Weldemichael et al., 2017).

3.2 Descriptive statistics and genetic parameters

3.2.1 Descriptive statistics

The output of the statistical analysis is shown in Table 2. The PH obtained a mean and a standard deviation of 2.47 ± 0.47 m and the range fluctuated between 1.54 and 3.71 m; TD varied between 3.02 and 7.11 cm; NBP ranged from 34.80 to 116.80; OIL presented values between 4.01 and 13.88 cm and the DPI was from 1 to 3.60. These variables determine the type of coffee growth and establish the prevalence of short and tall accessions, which would come to be derived from the genetic groups of Typica, Bourbon and hybrids (Anthony et al., 2002). In addition, Aguiar et al. (2004) argue that plants with lower size are generally more compact and productive, as for those with higher size, which can even be used as a selection criterion for breeding programs, since it is related to coffee productive potential. This is consistent with the findings in this study, for example, accession 37 was characterized by being compact, with a rigid trunk and short orthotropic internodes, presenting 1.54 m PH, 82.4 NBP and 5.37 kg FPP. While accession 9, with a non-compact appearance, has a very flexible main trunk, and distant orthotropic internodes, and register a PH of 3.58 m, NBP of 54 and FPP of 2.06 kg.

As for the characters related to the NFB, they stand out for their importance in plant productive potential, since they are responsible of maintaining the stability of production in the following years after the first harvest. The NFB is related to the LFB, NNB and LIN, and these in turn with the PH, NBP and OIL variables, jointly determining the archetype and performance of coffee plants. Our results indicate that the NFB obtained a range from 18.40 to 83.20, with a mean of 45.08; the LFB varied between 44.20 and 102.60 cm, with a mean of 67.12 cm; the NNB was from 7.40 to 23.60, with a mean of 14.09, and the LIN fluctuated between 3.10 and 9.70 cm, with a mean of 4.09 cm. The variations found in the quantitative characters LFB, NNB and LIN agree with what was reported by Adem et al. (2020), Berksisa et al. (2021); Atinafu and Mohammed (2017b) and Weldemichel et al. (2017) in diversity studies for coffee accessions in Ethiopia. Likewise, the great amplitude of these variables can be observed in the ranges shown by accessions 72 and 112, which presented means of 66.00 NFB, 23.60 NNB, 3.10 cm for LIN, and 21.60 NFB, 7.40 NNB, 9.70 cm for LIN, respectively. In fact, the differences were also noted at the productive level, where accession 72 obtained 3.81 kg and accession 112 barely reached 0.70 kg of FPP in five harvesting seasons. Therefore, the NNB and LIN variables have been widely used by coffee breeders and producers, in order to differentiate a very productive variety from a nonproductive one, hence, the higher NNB and the lower LIN, the greater the potential productivity of the node, structure where the flower buds differentiate to rise the development of the fruits. Consequently, it is possible to use this criterion as a reliable basis for preliminary identification of genotypes with high productivity traits. Following this criterion, considerable frequency of cases occurred in this study, where accessions were characterized by being short plants with many productive branches, short and very productive internodes, especially accessions 20, 26, 38, 46, 53, 54, 67 and 71.

Leaf character was evaluated through estimates of LA and PPD, these, in turn, can be used as productive indicators in the evaluation of genotypes, due to their contribution to the rate of growth and vegetative development, photosynthetic efficiency, evapotranspiration and the use of nutrients and water (Favarin et al., 2002; Unigarro et al., 2017). Accession 6 obtained the lowest LA, which consisted of 42.92 cm2, while accession 172 registered the highest LA, which was 251.23 cm2. On the other hand, accession 46 and 229 registered the minimum and maximum defoliations with 5.17 and 74.83%, respectively. Besides, accession 46 presented the higher productivity (8.52 kg), followed by accessions 172 (4.90 kg), 229 (3.35 kg) and 6 (1.14 kg). These results would indicate that, if a genotype maintains an active LA and a considerable number of leaves for a long time, it will be potentially more productive, and can be considered as a promising genotype.

For fruit and seeds characters, wide ranges of values were observed, obtaining means of 13.25 and 7.90 mm for FGD and SGD, respectively. For the FGD variable, 58.64% of the accessions estimated values between 18.43 and 13.00 mm, values that would be above what was reported for coffee cultivars, Catuaí (Ø = 13 mm), Costa Rica 95 (Ø = 14 mm) and Pacamara (Ø = 15mm). Regarding the SGD, the accessions that stand out significantly are 168, 163 and 158, which obtained means of 9.92, 9.76 and 9.65 mm, respectively. The results for SGD suggest that many accessions would present commercially exportable grains, since they border diameters greater than sieves of 17/64" (Ø = 6.75 mm) and 16/64" (Ø = 6.35mm). FGD and SGD variations establish the possibility of selecting accessions to improvement grain size character, and in turn, the physical yield, and the cup quality of the beverage.

Production characters and resistance to coffee leaf rust (*Hemileia vastatrix*) are highly desired traits in the selection process, that will allow identify advance genotypes for further

studies in a breeding program. Other traits of agronomic interest must be added, such as short plant, percentage of empty fruits below 5%, high percentage of commercial type grains and an active foliar area maintained for a long time. So, accessions 46, 53, 54, 38, 26, 71, 24, 67, 20, 27, 159 and 29 are the ones that stand out for the FPP variable, where means of 8.52 to 5.90 kg of cherry coffee were estimated in five harvesting seasons. Likewise, accessions 53 and 46 presented values of 9.96 and 10.83% for LRI and 0.06 for LRS variable; both accessions showed high values of LRI with a low LRS. In addition to the productivity and resistance variables, all the accessions presented acceptable PVF means; however, accessions 29 and 71 obtained large grain losses, being 10.33 and 17.93%, respectively. It should be noted that, if the estimation of the production per year is made in calculations of the value of dry parchment coffee per hectare, the aforementioned accessions would be able to position themselves with values above the national mean, according to what was reported for the 2019 – 2020 season of 752 kg/ha by USDA-FAS (2020).

Variables related to the phytosanitary status of the accessions presented extreme values, showing possible sources of resistance. The damage caused by the coffee berry borer (*Hypothenemus hampei*) and the leafminer (*Perileuoptera coffeella*) obtained infestation levels that did not exceed 40 and 80%, respectively. Although completely healthy plants were hardly found, the results offer the possibility of identifying genotypes with a lower degree of infestation, that could adapt to agricultural ecosystems in lowland areas that present sudden changes in their temperature and precipitation patterns, conducive to the development of pests. Finally, the use of genotypes with a certain degree of resistance could be part of technological packages in integrated pest management programs that focus on increasing productivity, reducing the use of insecticides, and preserving the environment.

3.2.2 Genetic parameters

Studying the diversity within a germplasm through the genotypic, phenotypic and environmental coefficients of variation (GCV, PCV, ECV), heritability (H) and variation index (VI) will let to know the nature and magnitude of the genetic action in the inheritance for a particular character; therefore, it allows the simultaneous selection of a greater number of characters that serve as a purpose to direct the selection towards superior genotypes (Ivoglo et al., 2008; Paw et al., 2020). The variation parameters found in this study are shown in Table 2. Values obtained for GCV and PCV were categorized as low (0 – 10%), moderate (10 – 20%) and high (greater than 20%), as proposed by Deshmuk et al. (1986). In relation to the categories described, the variables that presented high values of GCV and PCV were NFB, OIL, DPI, LA, FPP, PVF, PFB, LRI, LRS, LMI and PPD. Meanwhile, the LIN obtained values that varied from moderate to high for the GCV and PCV, respectively. In contrast, FGD and SGD were classified with low values for GCV and PCV. As for the rest of the variables, they showed moderate values. Also, it was observed that the PCV was slightly higher than the GCV, indicating that the characters are less influenced by the environment, that is, the genotype played a greater role in the expression of the character. Similar results have already been reported in other analyzes of coffee genotypes (Alemayehu, 2019; Atinafu et al., 2017; Cheserek et al., 2020; Merga et al., 2021; Weldemichael et al., 2017). The heritability (H) is considered as the ratio of the GCV and PCV, for a range of 0 to 100%, where values greater than 80% ensure a genetic gain (Falconer & Mackay, 2009; Ferrão et al., 2008). The variation index (VI) represents the relationship between the GCV and PCV, thus, it determines if the variability is due to genetic or environmental factors. When this value is close to 1, the variation is predominantly caused by the genotype. For this study, the

variables LIN, LA, FPP, SGD, PFB, LRI, LRS and PPD, are considered traits of agronomic interest, because they present values of VI greater than 1, and a higher H at 80%. So, these variables should be taken into account for coffee breeding programs, because they are probably characters highly transmitted from one generation to another (Dutra Giles et al., 2019; Ivoglo et al., 2008; Paw et al., 2020).

3.3 Correlation coefficient between agro-morphological variables

The analysis of the phenotypic and genotypic correlation coefficients for the 20 agro-morphological variables showed positive and negative associations for a significance level of 5% and 1%, respectively (Figure 1). With some exceptions, the magnitude of the association between the variables was higher for the genotypic correlation coefficient compared to the values shown by the phenotypic correlation coefficient. In addition, a greater number of significant associations was found for genotypic correlations. These results allow us to infer that the magnitude of the association between the characters is fundamentally due to the genetic properties of the material; thus, they are caused by pleiotropic effects of the genes or by genetic linkage (Falconer & Mackay, 2009).

Regarding coffee yield, it was observed that the phenotypic and genotypic correlation for the FPP variable was significant and positive with the variables NBP, NFB, NNB, LA, WHF, PFB and LMI. Similarly, the FPP was significantly and negatively correlated with the variables PH, LIN, OIL, SGD, LRI, LRS and PPD, both at the phenotypic and genotypic levels. A priori, these results would indicate that the increase in yield could be obtained through the improvement and simultaneous selection of the mentioned variables. Cerda et al. (2017) and Unigarro et al. (2017) indicate that the number of productive nodes, number of plagiotropic branches and leaf area are directly associated with the productive potential of the plant, and these characters should be considered as components of productivity. Interestingly,

the correlations of FPP with the variables PH, LIN, OIL, SGD, LRI, LRS and PPD, indicate the existence of accessions with resistance to coffee leaf rust that would be characterized by being short and compact plants, suitable traits that would lead to adopting the necessary strategies to establish a coffee genetic breeding program by increasing the number of plants per surface area in the various agricultural systems of the country. On the other hand, the breeder must be especially careful in the intention to improve the SGD through weight or volume, since, by being negatively associated with the FPP, it could lead to a gain in the weight or volume of the seed. Therefore, in case of negatively correlated variables, an independent selection is necessary, which could lead to the improvement the desired character. The results obtaining in this study agree with the reports of Weldemichael et al. (2019), Kifle et al. (2018), Atinafu and Mohammed (2017a) and Olika et al. (2011), who found that the relationship between coffee yield and its production components are usually expressed with positive and significant values.

Regarding the LRS variable, it showed a significant and positive association with the variables PH, LFB, LRI and PPD for the phenotypic and genotypic correlations, respectively. Similarly, the LRS at the phenotypic and genotypic level correlated significantly and negatively with the variables DPI, LA, WHF and LMI. The results suggest that the selection based on LRS variable would allow a substantial improvement in the LRI, PPD, LA and WHF variables, since, when selecting accessions with traits of resistance or tolerance to coffee leaf rust would be expected a reduction in the percentage of damage, loss of leaves, greater foliar surface and an increase in the weight of the fruits. This would confirm that the leaf area is an influential factor during the flowering and fruiting stage of coffee, since it is responsible of exporting the carbohydrates necessary for the weight gain of the fruit and grain (Marín-Garza et al., 2018; Rennie & Turgeon, 2009). The results obtained agree with those reported by Merga et al., (2019) who observed a positive correlation at the phenotypic and

genotypic level between the incidence of coffee leaf rust with plant height and plagiotropic branch length. On the other hand, Kifle et al. (2018) observed a negative association of coffee leaf rust incidence with plant height, plagiotropic branch length and leaf area for phenotypic and genotypic correlations.

Finally, this study highlights positive and negative correlations for the agro-morphological variables PH, TD, NBP, NFB, LFB, NNB, LIN and OIL, at both phenotypic and genotypic levels. Significant and positive relationships were observed for variable NBP with NFB ($P \leq 0.01$); OIL with LIN; LFB with PH and OIL with PH. The values obtained for these variables indicate that selecting accessions with a greater number of plagiotropic branches would improve the architecture of the coffee plant (short and compact) and the characters that make up the components of productivity.

3.4 Cluster analysis

Grouping of the accessions was developed using the Tocher optimization method (Table 3), adopting the genetic dissimilarity matrix obtained by estimating 19 agro-morphological quantitative variables based on the D^2 statistic or Mahalonobis generalized distance. The Mahalanobis distance is based on the covariance of the compared variables, and it has the advantage of using the group means and their variances and avoids the scaling and correlation problems inherent in the Euclidean distance (Li & Jain, 2015). These characteristics make the Mahalonobis distance a very robust method when measuring distances through quantitative variables. Likewise, it is considered the most useful method by breeders because it provides a rational basis for selection of promising genotypes for the development of hybridizations in breeding programs (Adem et al., 2020; Beksisa et al., 2021; Paw et al., 2020). Tocher's grouping method, based on the dissimilarity matrix, identifies the most similar pair of individuals and those that form the initial group; subsequently, it evaluates the possibility of a

new individual mean distance within the group that is smaller than that of any group. Thus, this method minimizes intragroup distances and maximizes intergroup distances (Dutra Giles et al., 2019).

The grouping also showed phenotypic variability among the accessions of INIA-CGC, dividing it into 10 groups or classes (Table 3). Most of the accessions clustered in group 1, with 133 accessions (82.10%). Group 2 gathered 10 accessions (6.17%), group 3 with 4 accessions (1.85%), group 4 had 5 accessions (3.09%), group 5 with 3 accessions (1.85%), group 6, 7 and 8 had 2 accessions each (1.23%) and group 9 and 10 were made up of only 1 accession (0.62%) each. The small groups show great divergence for their phenotypes. This pattern of size and number of groups has been previously observed in studies of *Coffea arabica* grouping using agro-morphological characteristics and indicates that there is a considerable phenotypic diversity among the coffee accessions under study. In Ethiopia, Atinafu and Mohammed (2017b) and Atinafu et al. (2017) grouped 124 genotypes into 10 groups using 10 agro-morphological traits, Weldemichael et al. (2019) grouped 49 genotypes into 5 groups, Beksisa et al. (2021) and Adem et al. (2020), classified 49 accessions into 3 and 5 groups, respectively. In Guatemala, Nakamura et al. (2013) grouped 44 accessions into 6 groups using Ward's method. In Saudi Arabia, Tounekti et al. (2017) also verified the presence of diversity, by grouping 19 accessions into 5 groups. Regarding the species *Coffea canephora*, in Brazil, using the same grouping method described for this study, Fonseca et al. (2006) grouped 32 genotypes into 12 groups using 7 characters; da Silva et al. (2015), meanwhile, grouped 17 genotypes into 13 groups, Covre et al. (2016) reported the grouping of 34 genotypes into 10 groups and, finally, Ivoglo et al. (2008) reported that 21 genotypes were grouped into 9 groups. Dutra Giles et al. (2019) grouped 34 genotypes of *Coffea arabica* and *Coffea canephora* into 10 groups by 10 morpho-anatomical characteristics.

The mean values of the agro-morphological characteristics for the 10 groups formed are shown in Figure 2. Group 1 presents a great amplitude in its evaluated characteristics, to facilitate its interpretation, it was divided into 23 subgroups. In general, the accessions of this group are mainly characterized by presenting variable levels of resistance to coffee leaf rust, they are also moderately productive, the fruits and grains are of medium size and weight, with a high level of damage by the coffee berry borer. From group 1, the accessions that are grouped in subgroups 1A (accession 20, 29, 38, 54, 67 and 71), 1D (accession 117), 1E (accession 24) and 1I (accession 26 and 27) stand out as future parents, because they present one or more characters of agronomic interest that could be selected simultaneously or independently to improve a particular character. The genotypes of the mentioned subgroups show tolerance to coffee leaf rust and values higher than the general average in terms of production. For example, accession 117 stands out for presenting complete resistance to leaf rust, but with a low productive performance. Group 2 is characterized by accessions with larger height and trunk diameter, few plagiotropic branches, distant internodes on the trunk and branches, good weight and size of fruit and grain, but with low production; they also have a high susceptibility and defoliation by leaf rust. Group 3 is made up of short plants, many plagiotropic branches, susceptible to leaf rust, and high defoliation. Group 4 is made up of medium-sized accessions, characterized by having the least number of plagiotropic branches, the greatest distance from internodes to the main trunk and in the productive branches, tolerance to leaf rust, but with productivity levels well below the general mean. Group 5 is made up of accessions that stand out among the most productive and resistant to leaf rust; they are characterized by being low growing plants with many plagiotropic branches, very short internodes on the productive branch, good weight and size of fruit and grain, low defoliation rate and high fruit loss due to coffee berry borer damage. These accessions can be considered as promising materials that should be included in breeding

programs. Group 6 brings together the tall accessions with a lower number of productive branches, less leaf area, greater loss of fruit by coffee berry borer, the lowest leaf area, low productivity, and a great loss of foliage due to high susceptibility to leaf rust. Group 7 shows the accessions that have the smallest trunk diameter, the shortest distance between internodes on the branches and main trunk, low production, low loss due to vain fruits and borer damage, and high susceptibility to leaf rust. Group 8 accessions exhibit the largest leaf area and vain fruits; they are also susceptible to leaf rust and have medium productivity. Group 9 is characterized by having the smallest fruit size and the largest grain size and tolerance to leaf rust. Interestingly, group 10 is made up only of accession 203, which must be selected to establish it as a parent for the generation of coffee hybrids. This accession brings together most of the desirable characters, thus presenting the greatest number of productive branches and nodes, the shortest length of internodes on the main trunk, greater weight of fruits, desirable grain size, low loss due to floating fruits, medium productivity, resistance to leaf rust with low rate of defoliation at the end of the harvest. Finally, the genetic divergence shown by the accessions of group 1 (1A, 1D, 1E and 1I), 5, 9 and 10 reveal a great opportunity to be selected and included in a program to breed Peruvian coffee, through the generation of hybrids or varieties of coffee of high productive and sanitary value, which are of commercial interest.

3.5 Principal component analysis (PCA)

PCA was developed to evaluate the relative importance of each characteristic in the variability of the studied accessions. The contribution of each character expressed as principal components (Eigen vector), the Eigen value, the proportion and the cumulative are shown in Table 4. The results indicate that keeping the first 5 principal components explains 70.01% of the total variation in the germplasm collection; likewise, the Eigen values for PC1,

PC2, PC 3, PC 4 and PC 5 were 4.30; 3.85; 2.49; 1.51 and 1.15, respectively. Similar observations were reported by Ndikumana et al. (2021), Berksisa et al. (2021) and Weldemichael et al. (2013) in exploratory analysis of genetic divergence between accessions of *Coffea arabica*.

Together, PC1 and PC2 accounted for 42.89% of the total initial variance, which can be explained based on the variables with the greatest weight within each component. For PC1, the variables with the greatest contribution were the OIL (-0.39), LIN (-0.33) and FPP (0.33); while for the second component (PC2) the variables LRS (0.35) and LRI (0.34) were the most relevant. The PC3 represented 13.09% of the variation, where the variables related to the size of the plant such as LFB (0.45), NBP (0.39) and PH (0.38) were the ones with the greatest contribution. PC4 explained 7.96% of the variation, where the variable PFB (0.65) contributed positively, and SGD (-0.52) contributed negatively to the component. As for the fifth component (PC5), accounted only for 6.08% of the total variation, in which the characters of FGD (0.70) and SGD (-0.35) contributed with polarized values as shown in the graphic representation of dispersion.

Interestingly, the variables with the highest value and close to one in the first two principal components would imply that these axes essentially measure the characters that correlate with plant size, productivity, and resistance to leaf rust; revealing that the grouping of the accessions is mainly influenced by the variables OIL, FPP, LRI and LRS (Ndikumana et al., 2021; Yan & Rajcan, 2002). In addition, this study highlights the most outstanding eigen vectors of PC3, PC4 and PC5 for contributing greatly to the differentiation of some groups and that is clearly seen in the scatter plots (Figure 3). In fact, the variables mentioned for the five principal components stand out for showing a high capacity for discrimination between the accessions, which is why it is suggested that these variables be considered as

tools for the selection process of parents in coffee breeding programs, since they will contribute to a significant improvement in production and resistance to leaf rust. However, the contribution of each variable is heterogeneous, varying according to the research and the genetics of the materials used; for example, in other coffee research using principal component analysis, Beksisa et al. (2021) observed that the variables related to branches and plant height were the ones that contributed the most to the first four components. Similarly, Weldemichel et al. (2013) reported that the length of the internodes in the main stem and productive branches contributed to PC1, while plant height and number of productive branches contributed more to PC2. On the other hand, Ndikumana et al. (2021) reported that the characteristics related to production and health contributed more to the variation of 15 accessions and 5 commercial varieties of *Coffea arabica*.

Scatter plots were elaborated based on the first five principal components, since they support the results obtained by the cluster analysis carried out using the Tocher method (Table 3 and Figure 3), in agreement with what was reported by Heydari et al. (2019) and Kumari et al. (2016). Dispersion graphs have been widely used to discriminate accessions in different crops (Aghaee et al., 2010), so that the study of their results together with the grouping analysis, are of great importance in breeding programs that they seek to adequately select the least related parents that come from distant groups and that contribute desirable alleles at different loci to the resulting progeny (Adem et al., 2020; Fonseca et al., 2006).

The use of dispersion graphs from PC1, PC 2, PC3, PC 4 and PC 5 allowed us to easily observe most of the groups and/or more distant accessions in the cartesian plane (Figure 3), especially promising accessions that are within group 1 (subgroup 1A, 1E, 1I), 5, 9 and 10, which stand out for their productivity and resistance to leaf rust. The graphical results would correctly indicate the relationships between the most relevant characteristics that made the

groups more divergent among the others. For this case, the combinations between the principal component 1 against 2 (Figure 3a) and the principal component 2 against 5 (Figure 3g) allowed us to identify the vast majority of groups, which are the largest and most distant, with the exception of the group 6 that graphically tends to overlap with groups 1 and 2. In addition, in Figure 3a, it is possible to discriminate the best and worst groups in terms of characteristics related to productivity and resistance to leaf rust, which in fact would correspond to the accessions that were located further from the point of origin of the perpendiculars of PC1 and PC2. Thus, the scatter plot shown in Figure 1a can be used as support for the selection of genotypes, considering the most important parameters of this study, such as production and resistance to *H. vastatrix*. At this point, Yan and Rajcan (2002) mention that selection should be focused based on the yield due to the ease of measurement and because it provides greater efficiency in the selection strategy. Thus, based on Figure 1a, the accessions contained in the fourth quadrant are the most outstanding, for presenting yields above the general mean and that, in addition, they have characters of commercial interest such as resistance to leaf rust. Among the most promising are accessions 46 and 53 that correspond to group 5, followed by accessions 38, 54, 20, 24, 26, 27, 29, 67, 71 and 159 that make up groups 1 (subgroup 1A, 1E and 1I) and 9, respectively. Likewise, it is important to mention accessions 110 (group 4), 117 (group 1, subgroup 1D) and 203 (group 10), which stand out for being highly resistant to *H. vastatrix*, but with low to medium production. Therefore, the identified promising accessions could be used as crossbreeding strategies with the aim of generating lines or varieties that simultaneously inherit the most important and commercially interesting traits or to broaden the genetic base of INIA-CGC. On the other hand, the accessions of groups 1 (accession 28 and 137), 2 (accession 9, 164, 157 and 228), 4 (accession 70 and 112) and 7 (accession 145) presented yields below the mean, because they were located at the furthest points with respect to the origin of the Cartesian plane. Likewise,

the information described can be corroborated just by looking at the scatter plot and considering these accessions as vertices to draw a polygon containing all the accessions.

In Figures 3b, 3c and 3d, the principal components relate to the variable OIL and the characteristics that make up the components of productivity. In this regard, figure 3b shows a consistent separation between the accessions that have the longest and shortest branch lengths, so that, at the ends of the first and fourth quadrants, the accessions with the shortest branch length are located, and in the second and third quadrant the accessions with greater branch length are located, respectively. Similarly, this graph can also discriminate between short and tall accessions, which can be explained by what was mentioned above. Similarly, in Figure 3c, the accessions of group 5 and 6 are shown as the most affected by coffee berry borer. The accessions of group 7, 8 and 9 exhibited the lowest values. Figure 3d highlights the accessions 4, 5 and 6 (group 3) with the highest FGD values. Accession 159 (group 9) had the smallest fruit diameter. Regarding Figure 3e, the accession 203 (group 10) stands out, due to its high level of tolerance to coffee leaf rust and because it has the greatest length of productive branches among all groups. In Figure 3f, it is possible to widely distinguish groups 6 and 7, since the first has high levels of damage by the coffee berry borer, and the second a low rate of damage. Figure 3g, 3i and 3j can clearly discriminate group 3 due to its large fruit size. These accessions could be selected for improvement of fruit and grain size. Finally, Figure 3h highlights accession 203 (group 10) for having the longest productive branch length, while accession 83 (group 6) presents high values of damage by coffee berry borer.

Some highly productive traditional varieties with high cup quality are currently marketed in the world, but many of them are susceptible to diseases and pests. For many years, studies have been carried out to improve the production, vigor and quality of plants in several

countries, such as India, Brazil, Colombia, Costa Rica, Kenya, Tanzania, Ethiopia, Angola and Portugal (van der Vossen et al., 2015). Crossing of divergent parents will promote maximum recombination and segregation of progenies and thus strengthen breeding programs (Tounekti et al., 2017). The agro-morphological characterization of 162 coffee accessions from INIA-CGC evidenced a wide range of phenotypic divergence, revealing potential genotypes for breeding programs, since the characteristics related to production and resistance to diseases could be improved, through selection and crossing, using divergent accessions with superior characteristics. Finally, these results are valuable in the Peruvian national context and, especially, in the Selva Central region, where the profitability of the product cannot be guaranteed to coffee families, due to the lack of technical assistance and infrastructure, which cause low production and poor management of pests and diseases (INIA, 2019). Therefore, INIA, responsible for this coffee germplasm collection, must maintain the conservation strategies that has been carrying out. Further studies at the molecular level of the accessions that make up this collection are necessary to determine their genetic diversity and population structure, as well as their varietal identification, that can be integrated to the agro-morfological data reported in this study for a better understanding of the INIA-CGC.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

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FIGURE LEGENDS

Figure 1. Pearson's correlation matrix for 20 agro-morphological characters evaluated in 162 coffee accessions from INIA's Coffee Germplasm Collection. Phenotypic correlation coefficient (upper diagonal). Genotypic coefficient of variation (lower diagonal). Significant at 5% (*). Significant at 1% (**). Plant height (PH). Trunk diameter (TD). Number of branches per plant (NBP). Number of fruit-bearing branches (NFB). Length of fruit-bearing branches (LFB). Number of nodes per branch (NNB). Length of internodes (LIN). Orthotropic internode length (OIL). Degree of plant inclination (DPI). Leaf area (LA). Fruit geometric diameter (FGD). Seed geometric diameter (SGD). Weight of a hundred fruits (WHF). Fruit production per plant (FPP). Percentage of vain fruits (PVF). Percentage of fruit affected by the coffee borer (PFB). Coffee leaf rust incidence (LRI). Coffee leaf rust severity (LRS). Percentage of leaf miner infestation (LMI). Percentage of plant defoliation (PPD).

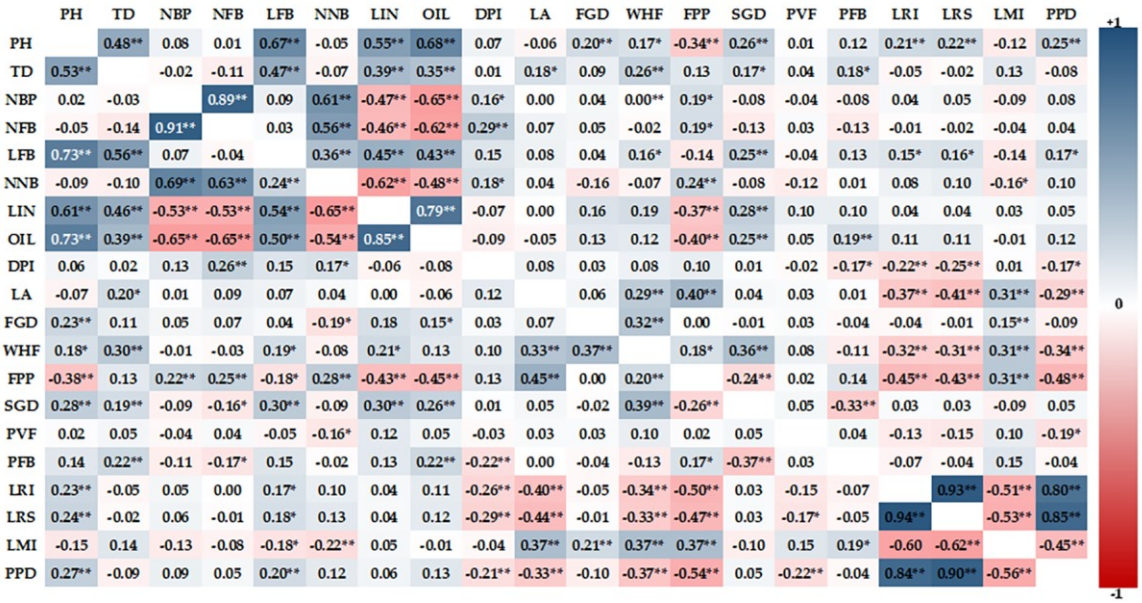


Figure 2. Mean values of 19 agro-morphological quantitative characters evaluated for 10 groups obtained by clustering 162 accessions of Coffea arabica from INIA's Coffee Germplasm Collection, with the Tocher method using the Malanohobis distance (D2). Plant

height (PH). Trunk diameter (TD). Number of branches per plant (NBP). Number of fruit-bearing branches (NFB). Length of fruit-bearing branches (LFB). Number of nodes per branch (NNB). Length of internodes (LIN). Orthotropic internode length (OIL). Leaf area (LA). Fruit geometric diameter (FGD). Seed geometric diameter (SGD). Weight of a hundred fruits (WHF). Fruit production per plant (FPP). Percentage of vain fruits (PVF). Percentage of fruit affected by the coffee borer (PFB). Coffee leaf rust incidence (LRI). Coffee leaf rust severity (LRS). Percentage of leaf miner infestation (LMI). Percentage of plant defoliation (PPD).

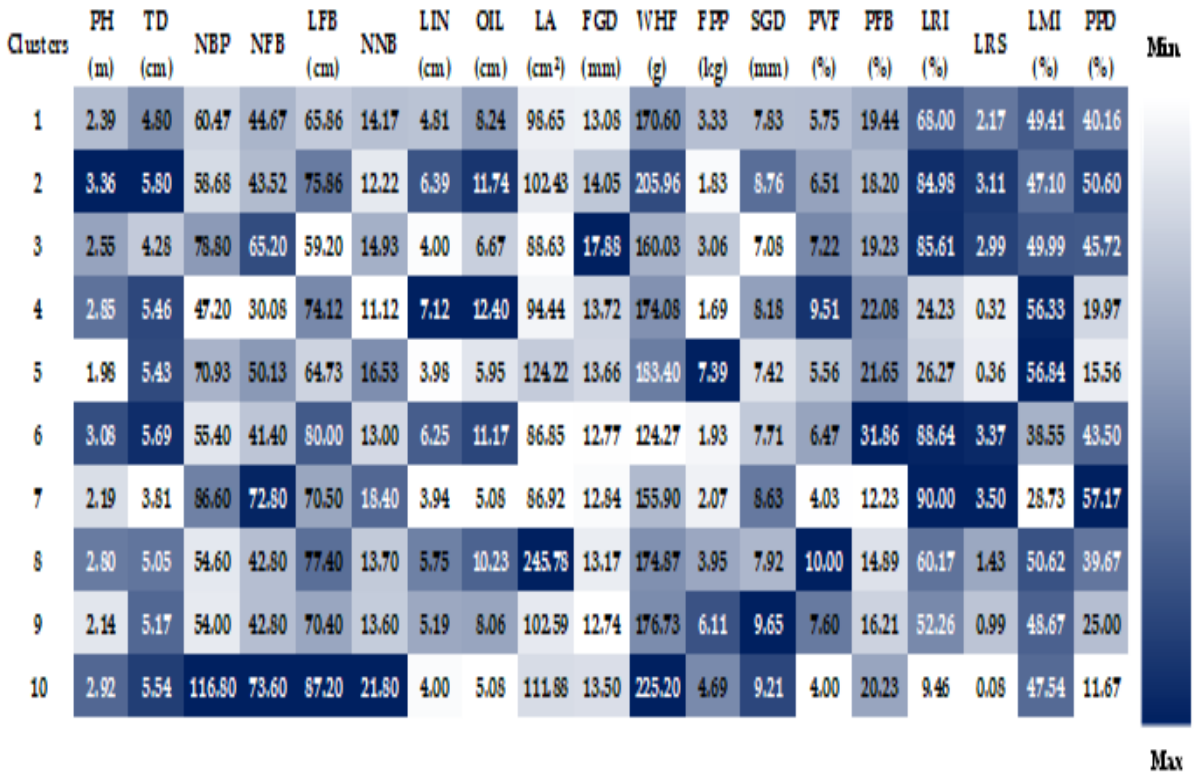
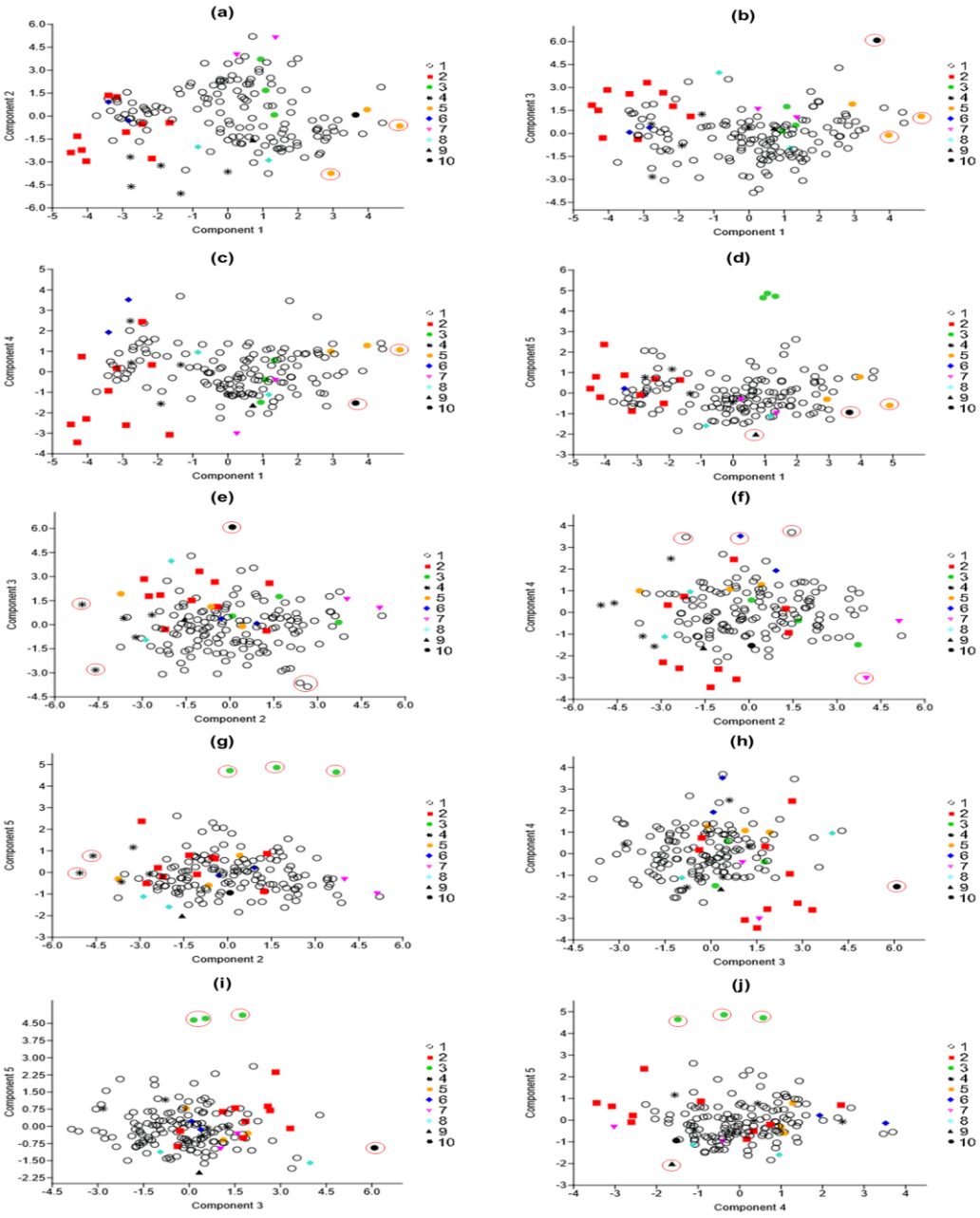


Figure 3. Dispersion graphs of 162 accessions of *Coffea arabica* from INIA's coffee germplasm collection, in relation to the first 5 principal components obtained from 19 agro-morphological quantitative characters. The red circles enclose the divergent accessions that present characters of commercial interest. (a) PC1 and PC2 scatter plot. (b) PC1 and PC3 scatter plot. (c) PC1 and PC4 scatter plot. (d) PC1 and PC5 scatter plot. (e) PC2 and PC3

scatter plot. (f) PC2 and PC4 scatter plot. (g) PC2 and PC5 scatter plot. (h) PC3 and PC4 scatter plot. (i) PC3 and PC5 scatter plot. (j) PC4 and PC5 scatter plot.



TABLES

Table 1. Analysis of Variance (ANOVA) for 162 accessions from *Coffea arabica* of INIA's Coffee Germplasm Collection evaluated according to 20 agro-morphological characters.

Mean squares											
Morphological characters											
SV	DF	TD	NBP	NFB	LFB	NNB	LIN	OIL	LA	FGD	SGD
Accession	161.00	2.98**	738.92**	847.04**	629.36**	36.96**	5.66**	22.76**	3091.08**	5.10**	3650.11**
Error	648.00	0.46	126.51	199.36	129.74	8.87	0.76	1.39	404.14	0.85	303.28
Agronomic characters											
SV	DF	PH	DPI	WHF	FPP	PVF	PFB	LRI	LRS	LMI	PPD
Accession	161.00	1.10**	1.73**	13.52**	1.51**	67.67**	181.44**	3507.16**	9.53**	441.12**	1361.67**
Error	648.00	0.07	0.46	1.74	0.08	12.26	26.73	148.89	0.31	129.59	129.59

Source of variation (SV). Degree of freedom (DF). Plant height (PH). Trunk diameter (TD). Number of branches per plant (NBP). Number of fruit-bearing branches (NFB). Length of fruit-bearing branches (LFB). Number of nodes per branch (NNB). Length of internodes (LIN). Orthotropic internode length (OIL). Degree of plant inclination (DPI). Leaf area (LA). Fruit geometric diameter (FGD). Seed geometric diameter (SGD). Weight of a hundred fruits (WHF). Fruit production per plant (FPP). Percentage of vain fruits (PVF). Percentage of fruit affected by the coffee borer (PFB). Coffee leaf rust incidence (LRI). Coffee leaf rust severity (LRS). Percentage of leaf miner infestation (LMI). Percentage of Plant Defoliation (PPD). Significant at 5% (*). Significant at 1% (**).

Table 2. Descriptive parameters and genetic variation for 20 agro-morphological characters evaluated in 162 coffee accessions from INIA's Coffee Germplasm Collection.

Variables	Mean ± SD	Min	Max	GCV%	PCV%	ECV%	H%	VI
PH (m)	2.47 ± 0.47	1.54	3.71	18.35	18.94	10.55	93.80	1.74
TD (cm)	4.89 ± 0.77	3.02	7.11	14.49	15.77	13.87	84.53	1.00
NBP	60.98 ± 12.16	34.80	116.80	18.15	19.94	18.45	82.88	0.98
NFB	45.08 ± 13.02	18.40	83.20	25.25	28.87	31.32	76.46	0.81
LFB (cm)	67.12 ± 11.22	44.20	102.60	14.89	16.72	16.97	79.39	0.88
NNB	14.09 ± 2.72	7.40	23.60	16.83	19.30	21.14	76.00	0.80
LIN (cm)	4.96 ± 1.06	3.10	9.70	19.95	21.44	17.56	86.58	1.14
OIL (cm)	8.51 ± 2.13	4.01	13.88	24.28	25.06	13.85	93.89	1.75
DPI	1.73 ± 0.59	1.00	3.60	29.16	34.01	39.16	73.49	0.74
LA (cm^2)	100.67 ± 24.86	42.92	251.23	23.03	24.70	19.97	86.93	1.15
FGD (mm)	13.25 ± 1.01	11.59	18.43	6.94	7.62	6.94	83.41	1.00
WHF (g)	172.61 ± 27.02	98.53	274.87	14.99	15.65	10.09	91.69	1.49
FPP (kg)	3.26 ± 1.64	0.25	8.52	47.12	50.46	40.46	87.14	1.16
SGD (mm)	7.90 ± 0.55	6.73	9.92	6.78	6.96	3.53	94.86	1.92
PVF (%)	5.98 ± 3.68	1.40	23.20	55.70	61.55	58.57	81.89	0.95
PFB (%)	19.48 ± 6.02	4.84	36.29	28.56	30.92	26.54	85.27	1.08
LRI (%)	67.22 ± 26.48	0.00	90.00	38.55	39.40	18.15	95.75	2.12
LRS	2.15 ± 1.38	0.00	4.00	63.05	64.10	26.01	96.71	2.42
LMI (%)	49.24 ± 9.39	25.77	77.68	16.57	19.08	21.13	75.46	0.78
PPD (%)	39.80 ± 16.50	5.17	74.83	39.44	41.46	28.60	90.48	1.38

Plant height (PH). Trunk diameter (TD). Number of branches per plant (NBP). Number of fruit-bearing branches (NFB). Length of fruit-bearing branches (LFB). Number of nodes per branch (NNB). Length of internodes (LIN). Orthotropic internode length (OIL). Degree of

plant inclination (DPI). Leaf area (LA). Fruit geometric diameter (FGD). Seed geometric diameter (SGD). Weight of a hundred fruits (WHF). Fruit production per plant (FPP). Percentage of vain fruits (PVF). Percentage of fruit affected by the coffee borer (PFB). Coffee leaf rust incidence (LRI). Coffee leaf rust severity (LRS). Leaf miner infestation (LMI). Percentage of plant defoliation (PPD). Standard Deviation (SD). Maximum (Max). Minimum (Min). Genotypic coefficient of variation (GCV). Phenotypic coefficient of variation (PCV). Environmental coefficient of variation (ECV). Heritability (H). Variation index (VI).

Table 3. Grouping of 162 accessions of *Coffea arabica* from INIA's coffee germplasm collection obtained by the Tocher method based on the Mahalanobis distance (D^2) using 19 agro-morphological quantitative characters.

Group	Subgroup	Number of accessions	Accessions
1	A	43	10 - 11 - 20 - 29 - 34 - 38 - 41 - 42 - 43 - 49 - 50 - 52 - 54 - 56 - 63 - 67 - 71 - 74 - 78 - 79 - 104 - 113 - 122 - 123 - 124 - 144 - 149 - 156 - 158 - 160 - 161 - 162 - 163 - 165 - 166 - 183 - 199 - 205 - 218 - 222 - 226 - 230 - 249
	B	35	12 - 15 - 18 - 22 - 31 - 44 - 45 - 60 - 61 - 66 - 68 - 73 - 76 - 77 - 80 - 81 - 105 - 108 - 114 - 119 - 136 - 138 - 139 - 141 - 143 - 147 - 150 - 152 - 155 - 167 - 168 - 229 - 233 - 236 - 248
	C	21	2 - 13 - 14 - 19 - 33 - 36 - 55 - 75 - 82 - 84 - 98 - 131 - 142 - 153 - 154 - 213 - 216 - 219 - 220 - 232 - 242
	D	5	39 - 47 - 65 - 117 - 130
	E	3	24 - 28 - 32
	F	2	35 - 174
	G	2	146 -214
	H	2	17 - 48

I	2	26 - 27
J	2	1 - 7
K	2	57 - 120
L	2	3 - 23
M	2	16 - 59
N	1	58
Ñ	1	8
O	1	30
P	1	64
Q	1	21
R	1	212
S	1	101
T	1	137
U	1	72
V	1	126

2	10	9 - 25 - 51 - 100 - 133 - 135 - 157 - 164 - 169 - 228
3	3	4 - 5 - 6
4	5	69 - 70 - 110 - 112 - 134
5	3	37 - 46 - 53
6	2	83 - 200
7	2	145 - 245
8	2	172 - 173
9	1	159
10	1	203

Table 4. Eigenvalues of the first five principal components (PC) for 19 agro-morphological quantitative characters used to classify 162 accessions of *Coffea arabica* from INIA´s coffee germplasm collection.

Variables	Principal Components				
	PC1	PC2	PC3	PC4	PC5
PH (m)	-0.32	-0.07	0.38	0.06	0.12
TD (cm)	-0.14	-0.20	0.33	0.20	-0.07
NBP	0.21	0.26	0.39	-0.05	0.18
NFB	0.24	0.24	0.35	-0.08	0.22
LFB (cm)	-0.23	-0.04	0.45	0.15	-0.22
NNB	0.18	0.26	0.35	0.12	-0.25
LIN (cm)	-0.35	-0.27	0.04	-0.01	0.07
OIL (cm)	-0.39	-0.25	0.00	0.09	-0.02
LA (cm²)	0.15	-0.21	0.17	0.02	-0.21
FGD (mm)	-0.03	-0.11	0.13	-0.18	0.70
WHF (g)	0.03	-0.27	0.25	-0.34	0.06
FPP (kg)	0.33	-0.12	0.11	0.22	-0.09
SGD (mm)	-0.15	-0.09	0.16	-0.52	-0.35
PVF (%)	0.02	-0.11	0.00	-0.06	0.25
PFB (%)	-0.04	-0.09	0.02	0.65	0.14
LRI (%)	-0.28	0.34	-0.02	0.00	0.07
LRS	-0.29	0.35	-0.01	0.02	0.09
LMI (%)	0.18	-0.31	0.01	0.06	0.15
PPD (%)	-0.27	0.34	0.00	0.01	0.01
Eigenvalue	4.30	3.85	2.49	1.51	1.15
Percentage (%)	22.61	20.28	13.09	7.96	6.08
Cumulative (%)	22.61	42.89	55.97	63.93	70.01

Plant height (PH). Trunk diameter (TD). Number of branches per plant (NBP). Number of fruit-bearing branches (NFB). Length of fruit-bearing branches (LFB). Number of nodes per

branch (NNB). Length of internodes (LIN). Orthotropic internode length (OIL). Leaf area (LA). Fruit geometric diameter (FGD). Seed geometric diameter (SGD). Weight of a hundred fruits (WHF). Fruit production per plant (FPP). Percentage of vain fruits (PVF). Percentage of fruit affected by the coffee borer (PFB). Coffee leaf rust incidence (LRI). Coffee leaf rust severity (LRS). Percentage of leaf miner infestation (LMI). Percentage of plant defoliation (PPD).