Journal of Sustainable Agriculture and Environment

WILEY

Global Initiative of Sustainable Agriculture and Environment
Harnessing Natural Resources

RESEARCH ARTICLE OPEN ACCESS

Association of Agro-Morphological Traits With Cup Quality in Accessions of *Coffea arabica* L. From the INIA Germplasm Bank, Peru

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Received: 10 October 2025 | **Revised:** 8 April 2026 | **Accepted:** 30 April 2026

Funding: Nacional de Innovación Agraria (INIA), within the framework, Grant/Award Number: 2480490; Mejoramiento de los Servicios de Investigación en la Caracterización de los Recursos Genéticos de la Agrobiodiversidad en 17 Departamentos del Perú (ProAgrobio)

Keywords: agro-morphological traits | *Coffea arabica* L. | cup quality | Peru | specialty coffee

ABSTRACT

In recent years, Peruvian coffee production has increasingly focused on specialty coffees, with cup quality (CQ) as a key criterion. While previous studies have characterized the Coffee Germplasm Collection of the National Institute of Agrarian Innovation (CGC-INIA), few studies have analyzed coffee cup quality. The present study assessed the association between agro-morphological traits and sensory quality of CGC-INIA. A total of 123 accessions from six departments were evaluated during two crop seasons (2022–2023 and 2023–2024). Fourteen agro-morphological traits (morphological, reproductive, and phytosanitary) and cup quality were recorded. Mean cup quality of the accessions was 81.56 points, which is classified as "very good" according to the Specialty Coffee Association. Most traits remained stable across seasons, except for fruit production and two phytosanitary traits (leaf miner infestation and rust incidence). Correlation analysis showed weak associations between individual agro-morphological traits and CQ ($r < 0.3$). Principal component analysis explained 28.6% of the total variance in the first two components, indicating limited overall association between agro-morphological variation and sensory quality. Generalized linear model results showed that Plant height (PH) and young shoot color (YSC) were the only traits positively associated with CQ. However, the weak associations and small effect sizes indicate that PH and YSC should be considered complementary indicators in CQ evaluation, and only within integrated selection frameworks that combine phenotypic, genetic, environmental, and management factors to improve specialty coffee quality.

Abbreviations: CBBI, Coffee berry borer infestation, %; CGC-INIA, Coffee Germplasm Collection of the National Institute of Agrarian Innovation; CLMI, Coffee leaf miner infestation, %; CLRI, Coffee leaf rust incidence, %; CQ, Cup quality, points; FC, Fruit color; FGD, Fruit geometric diameter, mm; FPP, Fruit production per plant, No. of fruits; FS, Fruit shape; GLM, Generalized linear model; INIA, National Institute of Agrarian Innovation; LA, Leaf area, cm^2; MHS, Mass of 100 seeds, g; PCA, Principal component analysis; PH, Plant height, m; PP, Peaberry percentage, %; SC, Sugar content, °Bx; SCA, Specialty Coffee Association; SGD, Seed geometric diameter, mm; YSC, Young shoot color.

Journal of Sustainable Agriculture and Environment, 2026; 5:e70173
https://doi.org/10.1002/sae2.70173

1 | Introduction

Coffee is the main agricultural export in Peru (Paredes-Espinosa et al. 2023), with a cultivated area of approximately 375,000 ha and more than 300,000 families involved in coffee production, processing, and trade, most of them smallholders located in regions such as Cajamarca, San Martín, Junín, and Amazonas (Gutiérrez 2024). Peru ranks ninth worldwide in conventional coffee production and remains a global leader in organic coffee (United States Department of Agriculture USDA 2025; Castillo Hijar 2023). This sector contributes significantly to the national economy by generating employment, promoting rural development, and strengthening exports. For the 2025/2026 marketing year, coffee production in Peru is forecast at 4.2 million 60-kg bags, reflecting an eight percent increase over the previous year (United States Department of Agriculture USDA 2025). Moreover, between 2019 and 2023, coffee exports from Peru reached a value of 829 million dollars, representing about 0.2% to the national domestic product (Ministerio de la Producción PRODUCE 2025). Since this crop has a key role in the national economy, it requires commitment of national institutions to quality coffee production, especially given the growing international demand for specialty coffees. Quality coffee production allows coffee farmers to obtain high prices, improve their livelihoods, and promote sustainable agricultural practices.

Cup quality (CQ) is a fundamental criterion in coffee selection and breeding programs (Leroy et al. 2006). It is determined through coffee cupping, a standardized procedure to evaluate ten sensory attributes, including fragrance/aroma, flavor, aftertaste, acidity, sweetness, balance, body, clean cup, uniformity, and overall quality. Each attribute is rated on a 6.0–10.0 scale, and the total score is calculated as the sum of all individual ratings (Specialty Coffee Association SCA 2025). According to the Specialty Coffee Association (SCA), coffees scoring above 80 points are considered "specialty". Within this category, they are further classified as very good (80–84.9), excellent (85–89.9), and outstanding (90–100) (Specialty Coffee Association SCA 2025).

Several factors influence CQ, including genetic variability, environmental conditions, and their phenotypic interactions; as well as agricultural management, processing methods (harvest and postharvest), and roasting, among others (Leroy et al. 2006; Bosselmann et al. 2009; Belchior et al. 2022; Bolka and Emire 2020). In this context, agro-morphological traits are a crucial component of the phenotype, and their relationship with CQ is complex and multifactorial, including associations with plant morphology, reproductive traits, and susceptibility to pests.

Morphological traits, such as plant height (PH) and leaf area (LA), influence the photosynthetic capacity and resource allocation, affecting seed size, density, and chemical composition; these traits are closely related to CQ (Silva Neto et al. 2018). Reproductive traits like seed diameter and mass of 100 seeds often reflect plant vigor and are associated with seed quality, with larger and heavier seeds generally achieving higher CQ scores (Hameed et al. 2018; Muschler 2001). A notable example is peaberry, a morphological variety with a single, rounded seed, often rated highly for CQ (Duque-Dussán et al. 2023).

The level of fruit maturity at harvest strongly influences cup quality. Volatile aromatic compounds and organic acids, which contribute to unique sensory attributes, accumulate progressively during ripening (de A. Silva et al. 2014; da Mota et al. 2020). Higher scores in these attributes are associated with improved CQ and higher international market prices (Vaast et al. 2006; Sanz-Uribe et al. 2017). During fruit ripening, sugars accumulate progressively, and sucrose alone can represent up to 73% of total seed sugars (Koshiro et al. 2015; Osorio Pérez et al. 2023).

The influence of phytosanitary traits on CQ is also important. Coffee berry borer (*Hypothenemus hampei* Ferrari) drills the fruits to reproduce inside the seeds (Moreno-Ramirez et al. 2024). As seed damage increases, beverage quality is negatively affected (Montoya, R. 1999). Coffee leaf rust (*Hemileia vastatrix* Berk. & Br) is characterized by the occurrence of yellow-orange powdery spores on the underside of leaves. Its progression causes premature leaf drop, reducing the photosynthetic capacity of the plant, which weakens the plants and leads to lower cherry production, ultimately affecting yield and potentially CQ (Documet-Petrlik et al. 2022). The coffee leaf miner (*Leucoptera coffeella* Guérin-Méneville) is a major pest that feeds on the mesophyll of coffee leaves, causing necrosis and reducing the photosynthetic surface. This damage leads to defoliation, weakens the plant, and affects flowering and fruit set, resulting in a significant reduction in seed production and quality (Dantas et al. 2021). These pests affect plant health and yield and can alter the physical and chemical composition of coffee beans, potentially leading to sensory defects and lower CQ (Ribeyre and Avelino 2012; Silva et al. 2024).

Germplasm banks play a key role in the conservation and improvement of the genetic diversity of plant species that are crucial for global food security and agricultural sustainability (Organización de las Naciones Unidas 2025). The CGC-INIA maintains 169 accessions from six regions of Peru, contributing to the development of sustainable agriculture. Therefore, in addition to the conservation and efficient management of these accessions, characterization and evaluation are required. In this sense, Paredes-Espinoza et al. (Paredes-Espinosa et al. 2023). analyzed the agro-morphological variability of these accessions by evaluating 20 vegetative, productive, and phytosanitary traits in the 2020–2021 crop season. Nevertheless, that study did not include a sensorial analysis of coffee. Although agromorphological traits have been characterized in the Peruvian coffee germplasm, their relationship with CQ remains poorly studied and scarcely documented. This lack of knowledge limits the identification of genetic materials with high-quality potential (Merga Sakata et al. 2022a).

The aim of this study was to assess the association between agro-morphological traits and CQ across two crop seasons (2022–2023 and 2023–2024), thereby advancing the characterization of Peruvian coffee germplasm.

2 | Materials and Methods

2.1 | Study Area

The study was conducted in the Pichanaki Agricultural Experimental Station, National Institute of Agrarian Innovation

(INIA), located in Pichanaqui district, Chanchamayo province, Junín region, Peru (10°55′29″ S and 74°52′36″ W; 774 m a.s.l.) (Figure 1). This station hosts the INIA Coffee Germplasm Collection (CGC-INIA), maintained under field conditions, established in 2015 with the support of the Korean Program of International Agriculture (KOPIA). Each accession is assigned a unique national accession code, registered in the Information System of Genetic Resources (SIRGE) of INIA, with detailed information available online through the GENEBANKPERU platform (https://genebankperu.inia.gob.pe).

2.2 | Crop Characterization

The CGC-INIA maintains 169 coffee accessions from six regions in Peru: Cajamarca (54), Amazonas (30), Huánuco (20), Pasco (25), Junín (34), and Ucayali (6) (Figure 1). The accessions were established under a diverse agro-forestry system characterized by the presence of native trees, including *Jacaranda copaia*, *Jacaratia digitata*, *Apeiba membranacea*, *Cedrelinga cateniformis*, *Tetragastris panamensis*, and *Inga edulis*. Climatic conditions were similar in both crop seasons. In crop season 1 (2022–2023) and crop season 2 (2023–2024), the mean temperatures were 26.50 ± 0.62°C and 26.54 ± 0.73°C, relative humidity was 74.41% and 74.01%, and the annual cumulative precipitation was 1625.4 mm and 1843.7 mm, respectively. The soil is classified as silty clay loam, with a pH of 4.1.

Each accession comprised ten 9-year-old coffee plants, spaced at 2.5 × 1.0 m between them, established in 0.42 ha (4023.8 plants/ha). Crop management practices included: (1) bimonthly mechanical weed control; (2) pest and disease control using preventive treatments for coffee berry borer, coffee leaf rust and coffee leaf miner. To control coffee berry borer, pitfall traps were set up all throughout the crop, every 20 m, at 1.5 m height, containing 1:1 coffee ground essence and alcohol (90°). Coffee leaf rust was controlled with Puccin® 77 WP copper hydroxide to the entire crop at a dose of 1 kg/200 L water, every 21 days (3 repetitions). Leaf miner control used alternating applications of Fipronil Regent® SC and OCAREN® (250 ml/200 L), at a dose of 250 ml/200 L water for both products, also every 21 days (3 applications). Plant fertilization began with the application of 100 g of dolomitic lime per plant before flowering to increase soil pH. Subsequently, a compound NPK fertilizer was applied at a rate of 250-50-250 kg/ha, based on a pre-fertilization soil analysis conducted at the INIA Soil Laboratory. This corresponds to approximately 80–100 g of fertilizer per plant, applied in three stages: before flowering, during fruit filling, and at the onset of maturation.

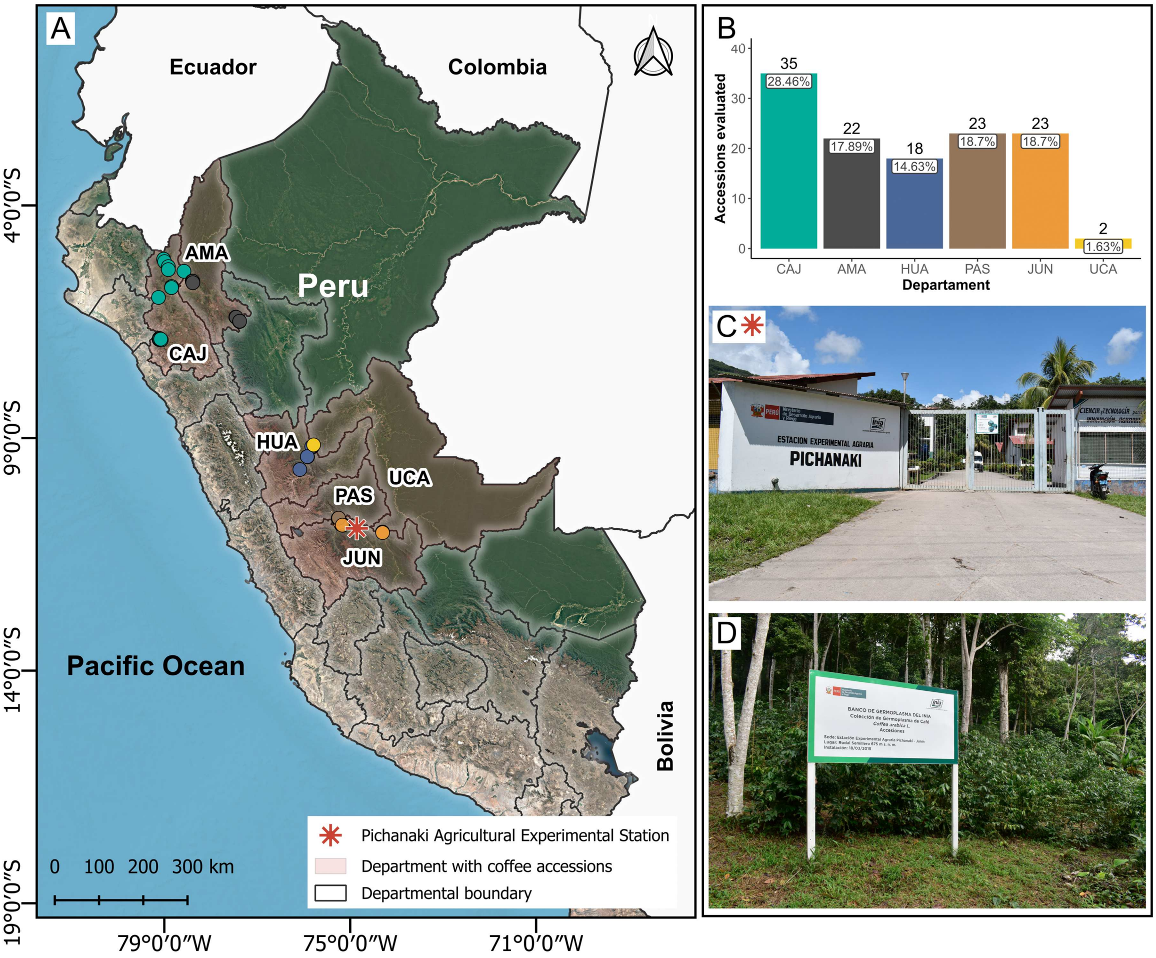


FIGURE 1 | (A) Map of provenances of coffee accessions incorporated into the INIA Germplasm Bank. Initials of departments were taken from 3166 to 2:PE ISO standard. (B) Percentage distribution of accessions evaluated by department ($n = 123$). (C) Front view of the Pichanaki Agricultural Experimental Station, Junín, Peru. (D) INIA Coffee Germplasm Collection.

2.3 | Methods

We studied 123 of the 169 accessions available; we excluded 19 accessions that exhibited intra-accession phenotypic heterogeneity, suggesting uncertain genetic identity or provenance, and 27 were not subjected to sensory evaluation due to inadequate production or storage conditions. Thus, we evaluated 22 accessions from the Amazonas region (17.89%), 35 from Cajamarca (28.46%), 18 from Huánuco (14.63%), 23 from Junín (18.7%), 23 from Pasco (18.7%), and 2 from Ucayali (1.63%). The evaluation was performed during two consecutive crop seasons: 2022–2023 (crop season 1) and 2023–2024 (crop season 2); each crop season started in July and ended in June of the following year. This study continued the work of the evaluation carried out by Paredes-Espinoza et al. (2023). During the (2017–2021 crop season), following pruning and reestablishment of agronomic management. After that assessment, we performed renewal pruning on the coffee plants. Once new shoots emerged, we implemented the previously described agricultural management practices.

2.4 | Agro-Morphological Traits

Five coffee plants of each accession were randomly selected, and 14 agro-morphological traits were measured: 3 morphological, 8 reproductive, and 3 phytosanitary descriptors. Most of the traits were measured using the method employed by Paredes-Espinoza et al. (2023). Agromorphological traits with greater representativeness were chosen, based on related studies, which could influence the quality of the cup of coffee. Traits that were not included in that study or that were measured using another method are described separately.

Quantitative morphological descriptors included plant height (PH), leaf area (LA), and Qualitative the young shoot color (YSC), which can be green or brown (see Figure 2A,B). The young shoot refers to the sprout emerging from dormant trunk buds (International Institute of Plant Genetic Resources IPGRI 1996).

Reproductive descriptors included six quantitative and two qualitative descriptors. The quantitative descriptors included: fruit geometric diameter (FGD); seed geometric diameter (SGD); fruit production per plant (FPP); mass of 100 seeds (MHS); peaberries percentage (PP), by weighing all the peaberries present in 100 g of parchment coffee; and sugar content (SC) measured from juice of 10 mature red fruits using a refractometer (HANNA HI96801) and reported in °Brix (Baptistella et al. 2024). The qualitative descriptors fruit color (FC) and fruit shape (FS) were assessed from 10 mature fruits per plant, using coffee descriptor standards (International Institute of Plant Genetic Resources IPGRI 1996). Coffee fruits can exhibit different colorations (FC): yellow, orange, red, purple, violet, and even black, while shapes (FS) can be classified as rounded, elliptical, obovate, ovate, or oblong.

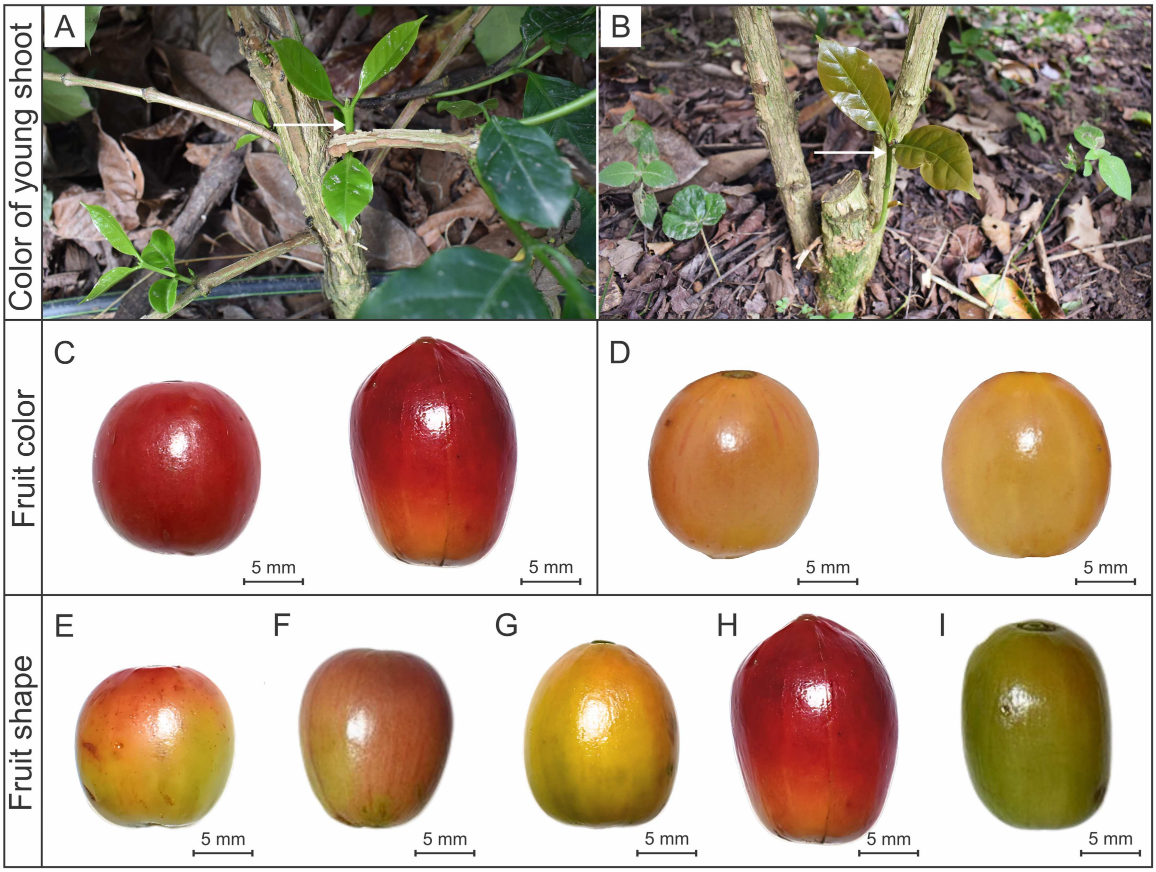


FIGURE 2 | Representative variation in (A–B) color of young shoot, (C–D) fruit color, and (E–I) fruit shape among coffee accessions. (A) Green young shoot, (B) Brown young shoot. (C) Fruit color red-purple, (D) Fruit color yellow-orange. (E) Fruit shape rounded, (F) Fruit shape obovate; (G) Fruit shape ovate, (H) Fruit shape elliptical, (I) Fruit shape oblong. Classifications of the three traits followed IPGRI descriptors.

The evaluation of phytosanitary descriptors included coffee berry borer infestation (CBBI), coffee leaf miner infestation (CLMI), and coffee leaf rust incidence (CLRI). For this purpose, 10 fruits or leaves per coffee plant were observed (collected from the upper, middle, and lower third of the plant), and the number of fruits or leaves with the presence of pests was counted. The infestation or incidence was calculated as the number of fruits or leaves with the presence of the pest/number of fruits or leaves assessed × 100, following the Servicio Nacional de Sanidad Agraria (SENASA) (Servicio Nacional de Sanidad Agraria SENASA 2017).

2.5 | Cup Quality Assessment

Evaluation of CQ was carried out through sensory analysis following the Specialty Coffee Association (SCA) Cupping Protocol, internationally recognized as the standard for classifying specialty coffees, by means of the sensory characterization of organoleptic attributes. For each accession, 55 g of medium-roasted coffee with medium grind size was used, divided into five replicates of 11 g each, brewed with 200 ml of water. The sensory analysis comprised the characterization of fragrance in dry ground coffee and, in infusion, the assessment of the attributes of aroma, flavor, aftertaste, acidity, body, balance, uniformity, cleanliness, and sweetness, across three temperature ranges: hot, warm, and ambient. Results were recorded on official SCA cupping forms, using a 0–10 scale for each attribute. The sum of scores allowed classification of the samples as outstanding (90–100 points), excellent (85–89.9 points), or very good (80–84.9 points). Coffees scoring below 80 were considered of good quality but did not qualify as specialty coffees (Specialty Coffee Association SCA 2025). The cup quality assessment was carried out at the Centro de Innovación Productiva y Transferencia Tecnológica Agroindustrial Oxapampa, of the Instituto Tecnológico de la Producción (CITE Agroindustrial Oxapampa – ITP), ensuring technical rigor and methodological reliability throughout the process.

2.6 | Statistical Analysis

All the statistical analyses were performed using the R Project version 4.5.2 (R Core Team 2025). Descriptive statistics were calculated for each crop season separately and for the combined dataset of both seasons, including mean ± standard deviation and ranges (minimum and maximum) for quantitative traits, and frequencies for qualitative traits.

We tested whether the measurements of the 11 quantitative agro-morphological traits met normality and homoscedasticity assumptions, with the aim of evaluating whether there were differences between crop seasons. The *t*-test for paired samples was applied when the statistical assumptions were met; Otherwise, the Wilcoxon test was used to ensure that normality was not observed in the differences between pairs. Additionally, to determine the magnitude of the differences between crop seasons, we calculated the effect size: Cohen's d for parametric data or Vargha and Delaney's A for non-parametric data.

The relationship between agro-morphological traits and CQ was measured through a Pearson's correlation matrix ($p < 0.05$), using the corrplot and ggplotify packages (Wei and Simko 2021; Yu 2023). A principal component analysis (PCA) was performed using the mean values of the 11 quantitative agro-morphological traits to identify the most important descriptors (i.e., the descriptors that most contributed to data variability) and to explore their association with CQ using the FactoMineR and factoextra packages (Lê et al. 2008; Kassambara and Mundt 2020).

To determine the agro-morphological traits associated with CQ, we used the average values of both crop seasons. We evaluated the normality of the data CQ through a plot, using the fitdistrplus package (Delignette-Muller and Duttang 2015) and the Akaike Information Criterion (AIC). CQ scores (ranging from 0 to 100 according to SCA protocols) were scaled to a 0–1 range to assess their fit to a beta distribution. Thus, CQ was modeled using generalized linear models (GLMs) with a beta distribution (logit link function), which were fitted using the glmmTMB package (Brooks et al. 2017). Subsequently, a full model was fitted, which included all agromorphological traits as explanatory variables, both quantitative (PH, LA, FGD, SGD, FPP, MHS, PP, SC, CBBI, CLMI, CLRI) and qualitative (YSC, FC). In the case of the YSC and FC, they were recoded as binary variables to include them in the model; except for FS, which did not have a consistent mode per accession in the database. This step was justified because the pairwise Pearson correlations between the predictors were low ($r < |0.7|$) (Dormann et al. 2013), and the influence of qualitative characteristics on CQ was unknown, so it was necessary to know those predictors (quantitative and qualitative) that are strongly associated with CQ. All predictor variables were centered and standardized to improve model performance and comparability of coefficients, as recommended by Schielzeth (Schielzeth 2010). The best-fitting model was identified using backward stepwise regression, an iterative process that begins with the full model and progressively removes one predictor at a time. At each step, reduced models were compared to the full model using likelihood ratio tests based on the Chi-square statistic (via the ANOVA function in R) to determine whether excluding a variable significantly reduced model fit. The procedure was repeated until only predictors that significantly contributed to explaining CQ remained in the final model (Inchausti 2022). Interpretation of model coefficients followed the “rule of 4” proposed by (Gelman et al. 2014).

We evaluated the validity of the best model by visually inspecting Dunn-Smyth residuals, which were obtained using the DHARMa package (Hartig 2016). The residual diagnostics did not reveal any clear violations from homoscedasticity or normality, suggesting that the model adequate fit to the data. The scripts or the command list used for all the analyses can be requested from the corresponding author.

3 | Results

3.1 | Agro-Morphological Traits

3.1.1 | Descriptive Statistics

Morphologically, coffee trees showed a PH of 2.24 ± 0.58 m (1.26–3.91 m). Leaf area (LA) averaged 69.45 ± 9.85 cm^2

(44.25–101.16 cm^2). For YSC, 41.46% of accessions showed green young shoots and 58.53% showed brown young shoots.

Among reproductive traits, FGD averaged 13.68 ± 0.70 mm (11.54–16.46 mm), and SGD averaged 7.54 ± 0.40 mm (6.36–9.46 mm). FPP averaged 605.02 ± 388.31 fruits (65–2605 fruits). MHS averaged 17.16 ± 1.88 g (13.29–26.13 g), PP averaged 6.73 ± 3.47% (1%–26.25%), and SC averaged 17.25 ± 1.57 °Bx (11.25–21.63 °Bx). For qualitative traits, FC was observed as red-purple in approximately 89.4% of the fruits evaluated and yellow-orange in 10.6%. FS was classified as rounded (48.37%), elliptic (36.18%), obovate (9.35%), oval (3.25%), and oblong (2.85%).

Among phytosanitary descriptors, CBBI averaged 6.54 ± 7.96% (0.00%–51.00%), CLMI averaged 15.05 ± 15.98% (0%–84%), and CLRI averaged 35.03 ± 27.25% (0%–100%).

3.1.2 | *Agro-Morphological Trait Variation Across Crop Seasons*

Of the 11 quantitative agro-morphological traits evaluated, eight presented significant differences between crop seasons (PH, FGD, SGD, FPP, PP, SC, CLMI, and CLRI) ($p < 0.001$), whereas three traits (LA, MHS, and CBBI) did not show such a pattern ($p > 0.05$). Mean values and standard deviation of the traits evaluated in each crop season are shown in Table 1.

Among morphological descriptors, PH exhibited statistically significant differences between crop seasons ($p < 0.01$); however, the effect size was small. LA did not present statistically significant differences ($p > 0.05$) (Figure 3A). These results indicate a relative consistency in morphological traits across both crop seasons.

The reproductive descriptors FGD, SGD, and FPP showed significant differences between crop seasons ($p < 0.01$), of intermediate effect size. PP and SC also exhibited significant differences, but the effect size was small ($p < 0.01$). MHS did not show significant differences between crop seasons ($p > 0.05$). These results show that, as in morphological traits, reproductive traits were relatively similar in both crop seasons (Figure 3B).

Among phytosanitary descriptors, CLMI presented statistically significant differences between crop seasons ($p < 0.01$), with a large effect size. Specifically, CLMI decreased approximately 6.8-fold, from 26.19 ± 15.24% in crop season 1 to 3.83 ± 5.43% in crop season 2. CLRI also presented significant differences between crop seasons ($p < 0.01$), with an intermediate effect size, showing a nearly two-fold reduction (46.17 ± 30.72 in crop season 1 vs 23.60 ± 16.43 in season 2). In contrast, CBBI did not show statistically significant differences between crop seasons ($p > 0.05$). These results indicate that CLMI was the only phytosanitary trait with a markedly distinct behavior between crop seasons, despite its high within-season variability (Figure 4A).

For fruit color, the proportion of red-purple and yellow-orange fruits was equal in both crop seasons, with 89% and 13%, respectively. This indicates that accessions producing a given fruit color in the first season maintained the same color in the second season (Figure 4A). Finally, regarding fruit shape, the most frequent category in crop season 1 was rounded,

TABLE 1 | Quantitative agro-morphological traits of 123 *Coffea arabica* accessions from the INIA germplasm collection were evaluated in two crop seasons.

N	Descriptor	Quantitative agro-morphological traits	Crop season 1 (2022–2023) Mean ± SD	Crop season 2 (2023–2024) Mean ± SD	Effect size
1	Morphological	Plant height PH (m)	2.21 ± 0.6 b (1.26–3.91)	2.26 ± 0.56 a (1.36–3.85)	0.46 (negligible)
2		Leaf area LA (cm^2)	68.86 ± 10.41 a (44.25–101.16)	70.05 ± 9.27 a (50.64–97.17)	0.48 (negligible)
3	Reproductive	Fruit geometric diameter FGD (mm)	13.47 ± 0.69 a (11.54–15.46)	13.89 ± 0.64 b (12.13–16.46)	0.33 (medium)
4		Seed geometric diameter SGD (mm)	7.43 ± 0.45 b (6.36–9.46)	7.65 ± 0.32 a (6.92–9.28)	0.33 (medium)
5		Fruit production per plant FPP (No. of fruits)	483.95 ± 270.72 b (68–1298)	726.09 ± 447.16 a (65–2605)	0.33 (medium)
6		Mass of 100 seeds MHS (g)	17.0 ± 1.94 a (13.29–25.76)	17.32 ± 1.81 a (14.03–26.13)	0.45 (negligible)
7		Peaberry percentage PP (%)	5.92 ± 3.12 b (1.00–15.86)	7.54 ± 3.62 a (2.80–26.25)	0.34 (small)
8		Sugar content SC (°Bx)	16.92 ± 1.64 b (11.25–20.94)	17.58 ± 1.42 a (13.81–21.63)	0.37 (small)
9	Phytosanitary	Coffee berry borer infestation CBBI (%)	6.89 ± 8.34 a (0.00–51.00)	6.19 ± 7.57 a (0.00–39.00)	0.55 (negligible)
10		Coffee leaf miner infestation CLMI (%)	26.23 ± 15.19 a (0.00–84.00)	3.87 ± 5.50 b (0.00–26.00)	0.94 (large)
11		Coffee leaf rust incidence CLRI (%)	46.13 ± 31.11 a (0.00–100.00)	23.92 ± 16.57 b (0.00–64.00)	0.71 (medium)

Note: Different subscript letters indicate statistically significant differences in agro-morphological traits between crop seasons ($p < 0.01$). Min and max refer to the minimum and maximum values observed, respectively.

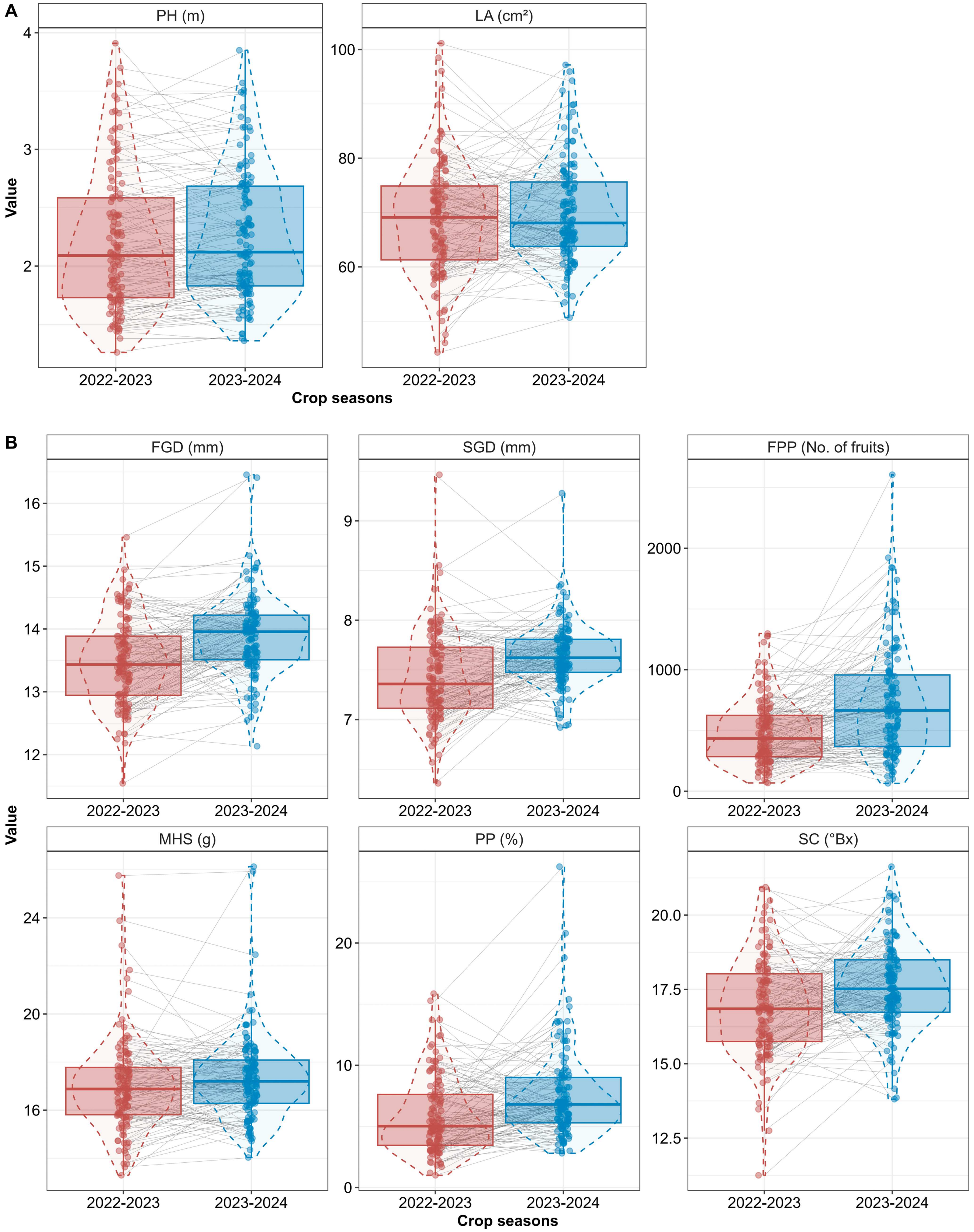


FIGURE 3 | Morphological and reproductive traits between crop seasons. (A) Comparison of the morphological traits PH and LA between crop seasons. For both PH and LA, the box plots showed similar medians, interquartile ranges, and overall data dispersion between crop seasons. (B) Comparison of the reproductive traits FGD, SGD, FPP, MHS, PP, and SC between crop seasons. For MHS, the box plots showed similar medians, interquartile ranges, and overall data dispersion between crop seasons, whereas FGD, SGD, FPP, PP, and SC exhibited slight increases in the 2023–2024 crop season. Dashed lines (violin plot) represent the density of kernel probability of the data for each trait and crop season. Gray lines represent the individual behavior of each accession in each crop season. All points are horizontally jittered by adding a random value to allow better visualization.

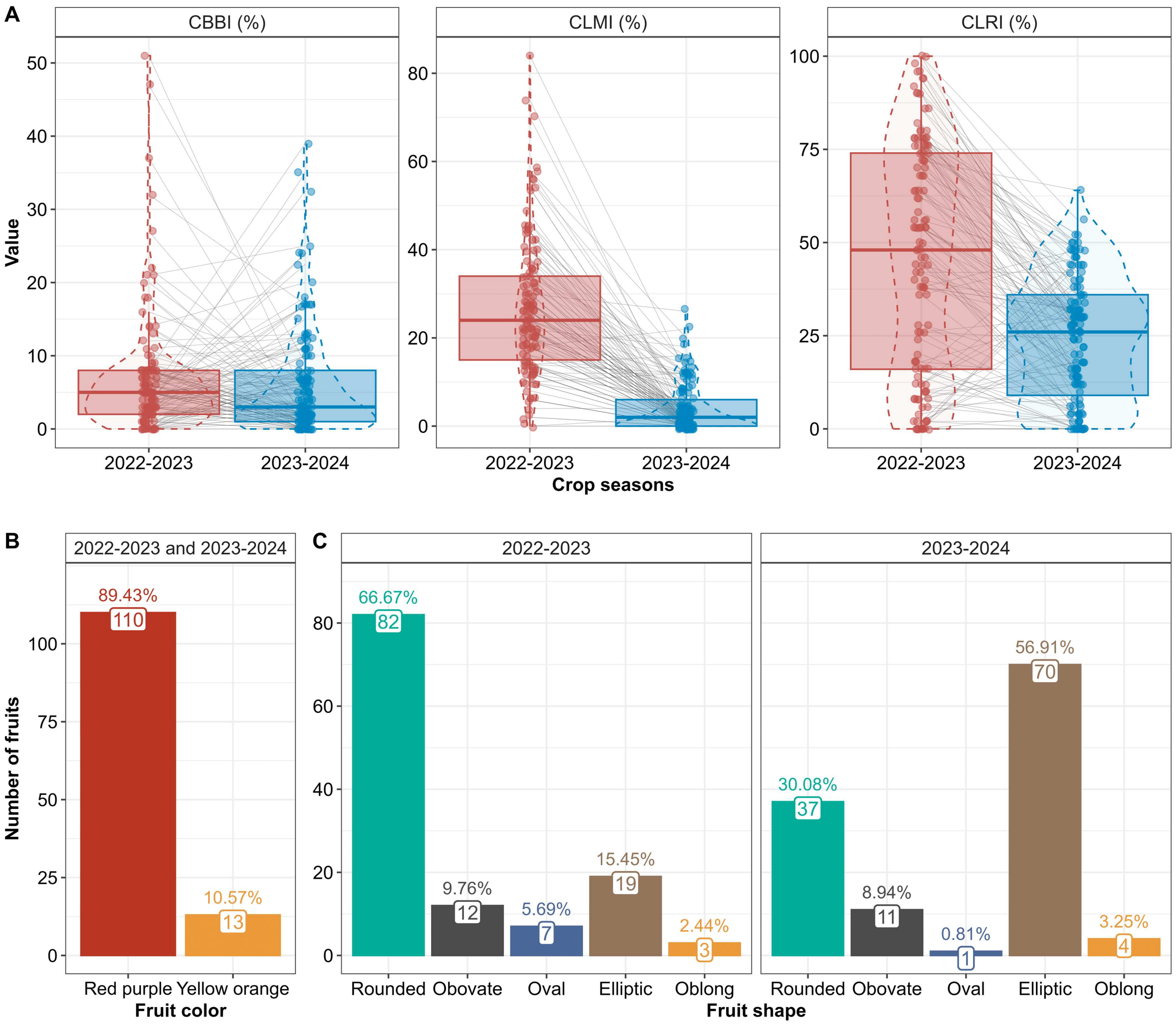


FIGURE 4 | (A) Comparison of the phytosanitary traits, coffee berry borer infestation (CBBI), coffee leaf miner infestation (CLMI), and coffee leaf rust incidence (CLRI) between crop seasons. CBBI remained stable between crop seasons, with boxplots showing similar median values, interquartile ranges, and overall data dispersion. In contrast, CLMI and CLRI showed a decrease in median values from the 2022–2023 to the 2023–2024 season. Dashed lines (violin plot) represent the kernel probability density of the data for each trait and season. Gray lines connect the same accessions across seasons, depicting longitudinal changes in individual performance. All points are horizontally jittered by adding a random value to allow better visualization. (B) Number of fruits classified by color (corresponds to the results of the 2 crop seasons). (C) Number of fruits classified by shape (corresponding to the results of each crop season).

followed by elliptical; together, these accounted for 82.12% of all fruits. In crop season 2, elliptical became the most frequent shape, followed by rounded, which together represented 87% of the total of fruits (Figure 4B).

3.2 | Cup Quality

3.2.1 | *Cup Quality and Crop Seasons*

The overall CQ averaged 81.56 ± 1.18 points. In crop season 1, CQ was 81.54 ± 1.19, while in crop season 2, it was 81.57 ± 1.17 points (Figure 5A). We did not record statistically significant differences in CQ between crop seasons ($p > 0.05$). In crop season 1, 111 accessions (90.24%) were classified as "specialty" coffee, with 110 classified as "very good" and one as "excellent". In crop season 2, 113 accessions (91.87%) were classified as "specialty", with all of them being "very good" and none being recorded as "excellent" (Figure 5B). Accession ACC128 was classified as 'excellent coffee' during crop season 1, achieving a cupping score above 85 points in accordance with SCA.

3.2.2 | *Relationships Between Agro-Morphological Traits and Cup Quality*

In the first crop season, CQ showed significant but weak positive correlations ($r < 0.3$) with PH, SGD, and MHS. In the second crop season, only PH maintained a consistent positive correlation with CQ, also weak in magnitude ($r = 0.23$),

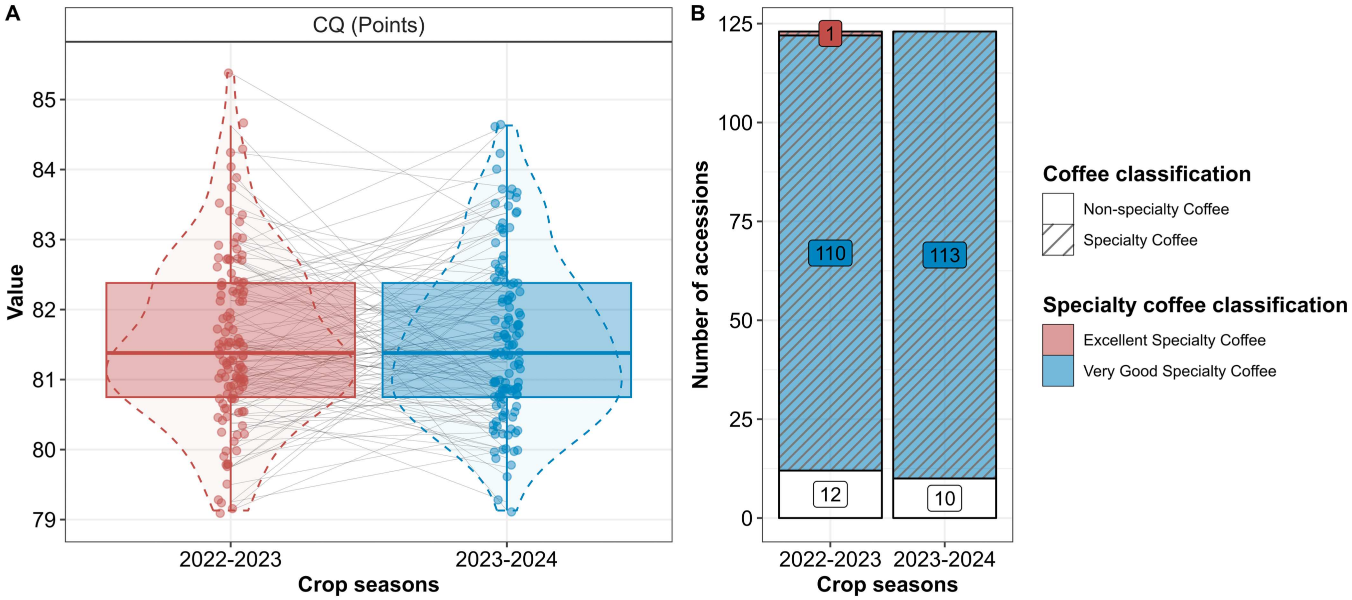


FIGURE 5 | Cup quality evaluated in two crop seasons. (A) Box plot of CQ for two crop seasons. CQ values showed no substantial differences between crop seasons, with similar medians, interquartile ranges, and overall data spread. Dashed lines (violin plot) represent the kernel probability density of the data for each trait and crop season. Gray lines connect the same accessions across crop seasons, depicting longitudinal changes in individual performance; all points are horizontally jittered by adding a random value to allow better visualization. (B) Classification of coffee accessions based on CQ scores following SCA standards: specialty coffee (≥ 80 points) is subdivided into "Very Good" (80–84.9) and "Excellent" (≥ 85 points). The number of accessions in each category is shown within the bars.

whereas the associations with SGD and MHS were not consistent between crop seasons and tended to be close to zero (Figure 6).

In addition to the associations with CQ, reproductive traits generally showed moderate positive correlations among themselves across both crop seasons, particularly between MHS, FGD, and SGD ($r = 0.32$–0.58). Phytosanitary traits showed moderate positive correlations between CBBI and CLMI, although this relationship was weaker in the second crop season. In contrast, SC did not show consistent or significant correlations with any trait across crop seasons (Figure 6).

Consistent with the correlation analysis, principal component analysis (PCA) showed a weak overall association between agro-morphological traits and CQ (Figure 7A). The first two principal components explained 28.6% of the total variance (PC1 = 16.7%, PC2 = 11.9%), indicating that the variability of the evaluated traits was distributed across multiple dimensions rather than concentrated in a few variables.

In the PCA biplot, CQ was oriented in the same general direction as PH and MHS, suggesting a possible positive association, although the angles between vectors were relatively wide, which is consistent with the low correlation coefficients observed in the previous analysis. Reproductive traits such as FGD, SGD, MHS, and PP were grouped in the same quadrant, showing closer relationships among these variables than with CQ. Phytosanitary traits (CBBI and CLMI) were projected in a different direction from CQ, suggesting no clear association with sensory quality (Figure 7A).

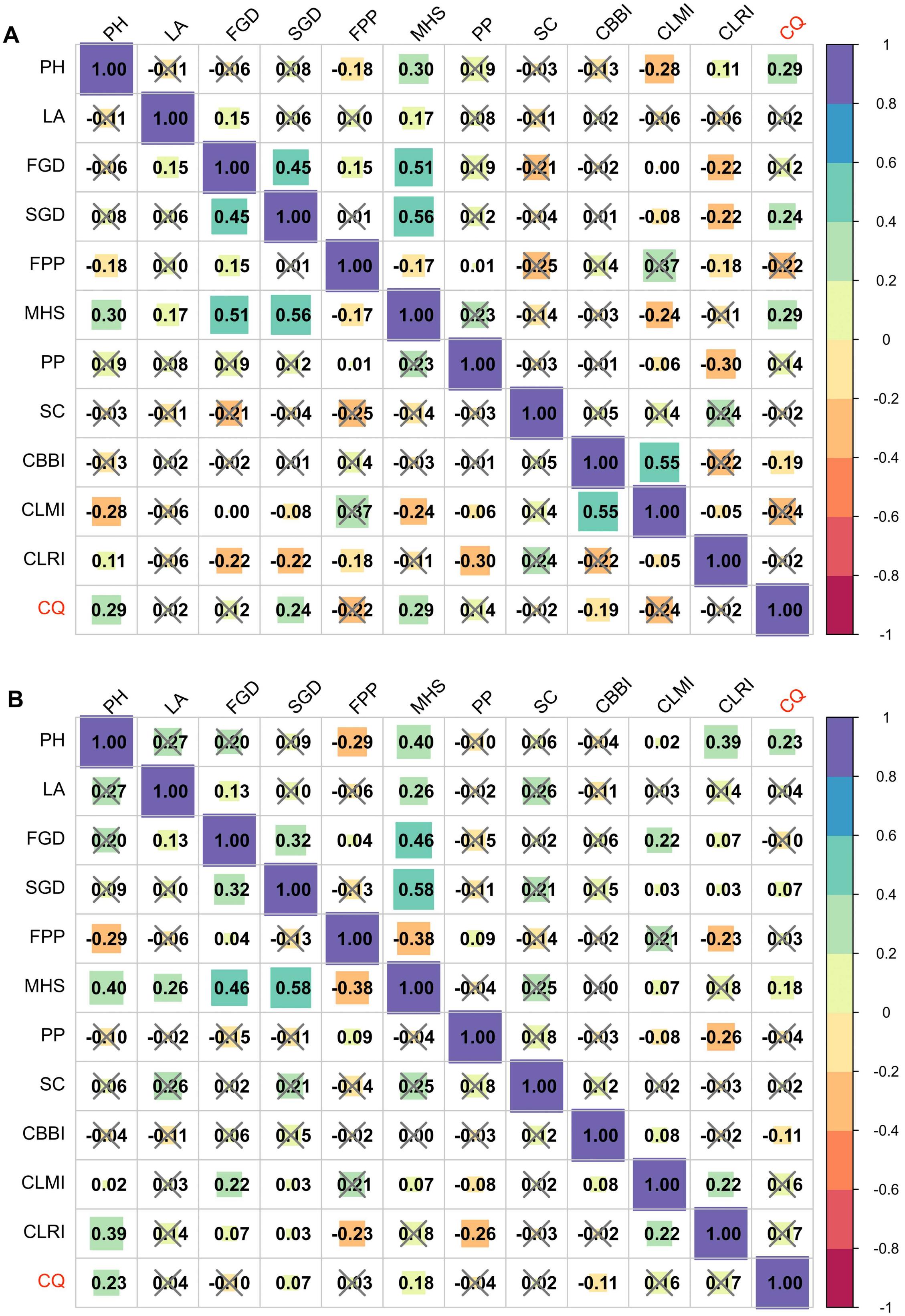
3.3 | Agro-Morphological Traits Predictive of Cup Quality

The generalized linear model (GLM) with beta distribution identified PH, FPP, MHS, and YSC as predictors retained in the best-fitting model (Table 2). However, only PH ($\beta = 0.015$, $p < 0.05$) and YSC ($\beta = 0.046$, $p < 0.001$) showed statistically significant effects on CQ, and the magnitude of these effects was small. In contrast, FPP and MHS remained in the final model but were not significant ($p = 0.09$ in both cases) (Table 2).

For PH, we found that for every 1 SD increase (equivalent to 0.58 m), a 0.37% increase of CQ is expected, which corresponds to an expected increase of approximately 0.51 points in average CQ (mean = 81.56 points) for every 1-meter increase in PH (approximate, Gelman's divide by 4 rules; see Statistical analysis). We also found that plants with green YSC reached higher scores than those with brown YSC. Plants with green YSC exhibited higher predicted CQ values (82.02 points) compared to plants with brown YSC (81.32 points), according to the model. Although statistically significant, these differences were small in magnitude, suggesting limited biological and practical relevance when considered individually. These relationships are illustrated in Figure 7B, where conditional plots predicted CQ as a function of PH and YSC with shaded areas representing the 95% confidence intervals.

4 | Discussion

Specialty coffee demand is increasing worldwide, highlighting the need to identify traits associated with sensory quality



A

	PH	LA	FGD	SGD	FPP	MHS	PP	SC	CBBI	CLMI	CLRI	CQ
PH	1.00	-0.11	-0.06	0.08	-0.18	0.30	0.19	-0.03	-0.13	-0.28	0.11	0.29
LA	-0.11	1.00	0.15	0.06	0.10	0.17	0.08	-0.11	0.02	-0.06	-0.06	0.02
FGD	-0.06	0.15	1.00	0.45	0.15	0.51	0.19	-0.21	-0.02	0.00	-0.22	0.12
SGD	0.08	0.06	0.45	1.00	0.01	0.56	0.12	-0.04	0.01	-0.08	-0.22	0.24
FPP	-0.18	0.10	0.15	0.01	1.00	-0.17	0.01	-0.25	0.14	0.37	-0.18	-0.22
MHS	0.30	0.17	0.51	0.56	-0.17	1.00	0.23	-0.14	-0.03	-0.24	-0.11	0.29
PP	0.19	0.08	0.19	0.12	0.01	0.23	1.00	-0.03	-0.01	-0.06	-0.30	0.14
SC	-0.03	-0.11	-0.21	-0.04	-0.25	-0.14	-0.03	1.00	0.05	0.14	0.24	-0.02
CBBI	-0.13	0.02	-0.02	0.01	0.14	-0.03	-0.01	0.05	1.00	0.55	-0.22	-0.19
CLMI	-0.28	-0.06	0.00	-0.08	0.37	-0.24	-0.06	0.14	0.55	1.00	-0.05	-0.24
CLRI	0.11	-0.06	-0.22	-0.22	-0.18	-0.11	-0.30	0.24	-0.22	-0.05	1.00	-0.02
CQ	0.29	0.02	0.12	0.24	-0.22	0.29	0.14	-0.02	-0.19	-0.24	-0.02	1.00

B

	PH	LA	FGD	SGD	FPP	MHS	PP	SC	CBBI	CLMI	CLRI	CQ
PH	1.00	0.27	0.20	0.09	-0.29	0.40	-0.10	0.06	-0.04	0.02	0.39	0.23
LA	0.27	1.00	0.13	0.10	-0.06	0.26	-0.02	0.26	-0.11	0.03	0.14	0.04
FGD	0.20	0.13	1.00	0.32	0.04	0.46	-0.15	0.02	0.06	0.22	0.07	-0.10
SGD	0.09	0.10	0.32	1.00	-0.13	0.58	-0.11	0.21	0.15	0.03	0.03	0.07
FPP	-0.29	-0.06	0.04	-0.13	1.00	-0.38	0.09	-0.14	-0.02	0.21	-0.23	0.03
MHS	0.40	0.26	0.46	0.58	-0.38	1.00	-0.04	0.25	0.00	0.07	0.18	0.18
PP	-0.10	-0.02	-0.15	-0.11	0.09	-0.04	1.00	0.18	-0.03	-0.08	-0.26	-0.04
SC	0.06	0.26	0.02	0.21	-0.14	0.25	0.18	1.00	0.12	0.02	-0.03	0.02
CBBI	-0.04	-0.11	0.06	0.15	-0.02	0.00	-0.03	0.12	1.00	0.08	-0.02	-0.11
CLMI	0.02	0.03	0.22	0.03	0.21	0.07	-0.08	0.02	0.08	1.00	0.22	0.16
CLRI	0.39	0.14	0.07	0.03	-0.23	0.18	-0.26	-0.03	-0.02	0.22	1.00	0.17
CQ	0.23	0.04	-0.10	0.07	0.03	0.18	-0.04	0.02	-0.11	0.16	0.17	1.00

FIGURE 6 | Relationship between agro-morphological traits and cup quality. (A) Crop season 1 and (B) Crop season 2. The boxes show the correlation values, which can be significant (positive or negative) or non-significant. The significant values have a color tone that ranges from intense blue (positive) to intense red (negative), which indicates a strong degree of association, and this is lower as the intensity of these colors decreases. Non-significant values are represented with a cross in the box, generally white and sometimes faint in color. Overall, most correlations with cup quality were weak ($r < 0.3$), indicating limited strength of association between individual agro-morphological traits and sensory quality.

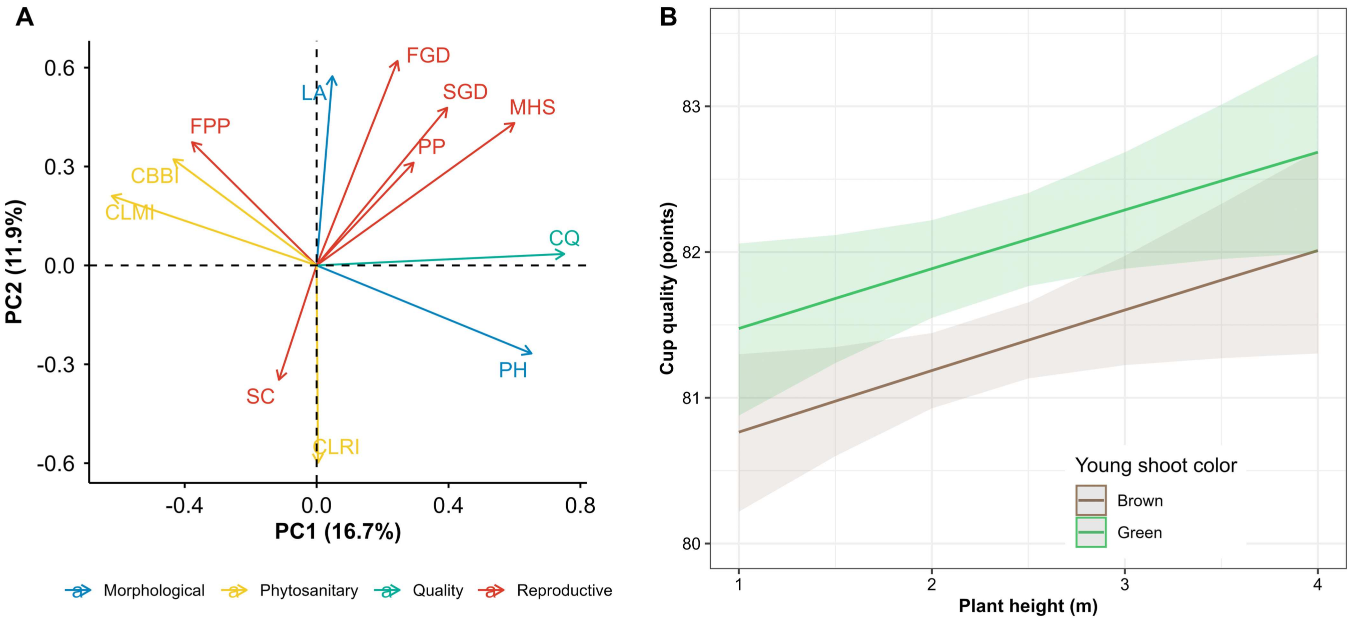


FIGURE 7 | (A) Principal component analysis of agro-morphological traits and cup quality. Arrows represent the direction and contribution of each agro-morphological trait, while colors indicate the type of descriptor (morphological, phytosanitary, reproductive, or quality). Traits with arrows pointing in similar directions suggest positive associations, whereas arrows pointing in opposite directions suggest negative associations. Approximately perpendicular arrows indicate weak or no association. The first two principal components explained 28.6% of the total variance, indicating a limited representation of the overall variability in the dataset. (B) Conditional plots from a beta GLM (logit link) showing predicted coffee cup quality (CQ in points) as a function of plant height (PH, in meters) and young shoot color (YSC). Shaded areas represent 95% confidence intervals.

TABLE 2 | Results of the beta GLM (link=logit) of coffee cup quality in relation to plant height, fruit production per plant, mass of 100 seeds, and young shoot color.

Parameter estimates	Estimate	Standard error	CI 95%	*Z* value	Pr(>|*z*|)
Intercept	1.471	0.008	[1.46, 1.49]	181.58	< 0.001***
PH	0.015	0.007	[0.001, 0.029]	2.11	0.03*
FPP	0.012	0.007	[−0.002, 0.026]	1.66	0.09
MHS	0.013	0.008	[−0.002, 0.028]	1.68	0.09
Green YSC	0.046	0.014	[0.019, 0.073]	3.43	< 0.001***

Note: The intercept represents the estimated CQ (on the logit scale) for plants with brown YSC, assuming mean values of PH, FPP, and MHS. The coefficients for PH, FPP, and MHS indicate how much the cup quality score (on the logit scale) changes with a one standard deviation increase in each trait. The coefficient for green YSC represents the difference in estimated CQ between plants with green and brown YSC. Asterisks denote significance levels:
$^{*}p \le 0.05$; $^{**}p \le 0.01$; $^{***}p \le 0.001$.

(Pérez-Molina et al. 2021; Merga Sakata et al. 2022a). In this study, the sensory quality of the 123 accessions was classified as very good, confirming the high potential of the INIA Coffee Germplasm Collection. Agro-morphological traits were associated with cup quality, but these relationships were weak and not fully consistent between crop seasons, with PH and YSC being the only significant predictors. These results suggest that agro-morphological traits may assist in germplasm characterization as auxiliary indicators within integrated selection frameworks that combine phenotypic, genetic, and environmental data, rather than as independent selection criteria.

4.1 | Agro-Morphological Trait Variation Across Crop Seasons

Of the 14 agro-morphological traits evaluated in this study, seven traits (PH, LA, FGD, SGD, CBBI, CLRI, and CLMI) were previously evaluated by Paredes-Espinoza et al. (2023), corresponding to the first five crop seasons (2017–2021) for morphological and reproductive evaluation; and one crop season (2020–2021) for phytosanitary evaluation. In our study, PH was 23 cm lower and LA was 31.22 cm^2 smaller than the values reported in that study; these reductions may be explained, at least in part, by differences in fertilization between studies. Paredes-Espinoza et al. (2023) applied a combination of fertilizers based on NPK, and supplementation with the hormones, auxins, gibberellins, and cytokinins, whereas we used only NPK. In this regard, Matamoros-Quesada et al. (2020) reported that the combined application of phytohormones and fertilizers promotes vegetative growth in *Coffea arabica* hybrids. Additionally, the lower values observed in our study are likely related to renewal pruning, as the evaluated accessions were regrowths. After drastic pruning, coffee plants enter a recovery phase in which growth is initially directed toward shoot regeneration rather than structural expansion, resulting in reduced plant height and leaf area during the early stages of reestablishment (Morais et al. 2012).

Neither FGD nor SGD presented differences with respect to the values reported by Paredes-Espinoza et al. (2023). (FGD: 13.68 mm vs 13.25 mm; SGD: 7.54 mm vs 7.90 mm, respectively). In contrast, differences were evident when comparing phytosanitary traits, with more effective control observed in the present study. Indeed, we recorded less than one-third of the CBBI value (6.89% *vs.* 19.48%), and about 50% lower values of CLMI (26.23% *vs.* 49.24%) and CLRI (46.13% *vs.* 67.22%) with respect to the values obtained by Paredes-Espinoza et al. (2023). This result might be attributed to the implementation of phytosanitary measures targeting these three pests. In this context, pest incidence in coffee systems has been associated with management practices, particularly pruning and shade regulation, where inadequate management can favor higher pest and disease levels (Harelimana et al. 2022).

Across crop seasons, variation in agro-morphological traits was also observed, with eight of the 11 quantitative traits showing statistically significant differences between crop seasons. However, in most cases, the effect size was small or moderate, suggesting a relative stability of agronomic behavior. In particular, FPP exhibited an increase of more than 200 fruits in crop season 2, coinciding with approximately 13% higher precipitation compared to crop season 1 (1843 mm vs 1625 mm). Adequate water availability can favor vegetative growth and fruit set by improving soil moisture conditions. Previous studies have reported that the effect of precipitation on coffee productivity depends on the phenological stage, with rainfall before flowering promoting fruit formation, whereas water deficit during fruit development may limit yield (Crasque et al. 2025; Parada-Molina et al. 2025). Therefore, the higher precipitation recorded in crop season 2 may have contributed to the greater fruit production observed.

In terms of phytosanitary traits, CBBI was similar between crop seasons, while CLMI and CLRI showed a marked reduction in the crop season 2. Although studies suggest that both CLMI and CLRI tend to increase with higher precipitation and humidity (Dantas et al. 2021; Bebber et al. 2016), the elevated precipitation recorded during crop season 2 may have mitigated thermal stress associated with the high average temperature (26.5°C). This is particularly relevant considering that the INIA Coffee Germplasm Collection is located at only 774 m a.s.l., an altitude where both rust and insect pests are typically more prevalent, especially when temperatures exceed 21°C (DaMatta 2004; Góngora et al. 2023). In comparison, elevations between 1000 and 1600 m a.s.l. are generally considered optimal for Arabica coffee cultivation (Hanan et al. 2024).

4.2 | Cup Quality

Even though the evaluated accessions were grown at a relatively low altitude (774 m a.s.l.), their sensory quality was comparable to reports from high-altitude coffee-producing regions of Peru (Cuzco, Amazonas, San Martín), supporting their potential as genetic resources for specialty coffee production (Rosario Márquez et al. 2020; Huaman Haro 2025; Guevara-Sánchez et al. 2019). No significant differences in CQ were observed between crop seasons, indicating a good sensory stability over time. Notably, one accession exceeded 85 points in crop season 1, reaching the "excellent" category. This finding suggests that this accession may have potential for use in breeding programs focused on high-quality coffee. This highlights the importance of multi-seasonal monitoring and sensory assessment to identify accessions with consistent quality for breeding programs (Tassew et al. 2021).

4.3 | Relationships Between Agro-Morphological Traits and Cup Quality

The correlation analysis revealed generally weak associations between agro-morphological traits and CQ across both crop seasons, a pattern that was consistent with the PCA, which explained a limited proportion of the total variance. In this context, PH was the only trait that showed a consistent, although weak, positive association with CQ across both crop seasons, a pattern also supported by its orientation in the PCA. In contrast, seed-related traits such as SGD and MHS showed weak correlations with CQ in the first crop season, but these associations were not stable over time and tended to disappear in the second crop season. Likewise, CQ did not show a clear association with phytosanitary traits, a pattern also reflected in the PCA. This contrasts with previous studies that have reported a direct influence of crop health on sensory quality (Montoya R. 1999; Ribeyre and Avelino 2012). Similarly, FPP did not show a significant relationship with CQ, as reported by Duque-Dussán et al. (2023). Overall, these results indicate that agro-morphological traits have a limited and inconsistent capacity to explain variation in CQ.

Comparable findings have been reported in other studies, although with varying patterns depending on species and genetic background. For instance, Zambrano-Flores et al. (2018) reported negative associations between cup quality and bean size, as well as with several organoleptic attributes in *Coffea canephora*, suggesting that larger grains do not necessarily translate into superior sensory quality. In contrast, Merga et al. (2022a) found no significant correlations between cup quality and agro-morphological traits such as plant height, number of nodes, fruit number, or grain characteristics in *Coffea arabica*, a result that is consistent with our findings. Similarly, Kathurima et al. (2009) reported non-significant relationships between sensory attributes and green bean characteristics in Arabica coffee from Kenya. However, other studies have indicated that the relationship between morphology and cup quality may exist, but is not uniform. For example, Kumar et al. (2012) suggested that certain morphological traits, such as internode length, leaf size, stem thickness, and cluster compactness, may act as phenotypic indicators of quality, while yield-related traits (e.g., fruit number and fruit or bean weight) may be associated with specific beverage components. In line with this, Perez-Molina et al. (2021) reported that some leaf morphoanatomical traits may also serve as informative indicators of cup quality, although these associations were weak and strongly influenced by environmental conditions. Taken together, these contrasting findings support the notion that the relationship between agro-morphological traits and cup quality is context-dependent and generally weak, which is consistent with the patterns observed in this study.

This pattern can be explained by the widely recognized complex and multifactorial nature of coffee quality (Góngora et al. 2023; Parada-Molina et al. 2022; Kath et al. 2021). Cup quality results from the interaction of genetic, environmental, and management-related factors, including elevation, soil properties, harvesting practices, biochemical composition, and post-harvest processing conditions (Rosario Márquez et al. 2020; Romano et al. 2022; Tesfa 2019; Haro et al. 2025). In addition, processing variables such as roasting temperature, time, and particle size can significantly alter sensory attributes (Bolka and Emire 2020; Getaneh et al. 2020), while agroforestry systems with shade trees can improve microclimatic and soil conditions that indirectly influence quality (Silva Neto et al. 2018; Haro et al. 2025). Therefore, the weak and inconsistent associations observed in this study likely reflect that CQ is determined by multiple interacting processes that extend beyond plant-level agro-morphological traits.

Beyond their relationship with CQ, reproductive traits showed moderate positive correlations among themselves. A similar pattern was reported by Paredes-Espinoza et al. (2023), who found positive correlations among fruit- and seed-related traits, including FGD-MHS ($r = 0.32$) and SGD-MHS ($r = 0.39$). Likewise, consistent with our findings, Paredes-Espinoza et al. (2023) reported strong correlations among phytosanitary traits, particularly between CLRI and CLMI. In contrast, SC did not show consistent or significant correlations with CQ or other traits, in agreement with previous studies (de A. Silva et al. 2014; Baptistella et al. 2024), indicating that this variable alone may not adequately capture the biochemical complexity underlying sensory quality.

4.4 | Agro-Morphological Traits Predictive of Cup Quality

The beta GLM identified PH and YSC as significant predictors of CQ, although the effect sizes were small. Specifically, for each 1 m increase in plant height, CQ increased by approximately 0.51 points, while accessions with green YSC consistently achieved higher sensory scores. The identification of PH as a significant predictor is consistent with the correlation and PCA results, where this trait showed a stable, although weak, association with CQ across crop seasons. Notably, although FPP and MHS were retained in the model, they were not statistically significant, despite having coefficients of similar magnitude to PH, suggesting that their contribution to CQ may depend on their interaction with other variables rather than acting as independent predictors. Overall, these results emphasize the importance of distinguishing between exploratory associations and predictive modeling approaches, as most previous studies have relied on correlation or multivariate exploratory analyses, whereas our approach allows the identification of traits with statistically supported predictive value. Nevertheless, the small effect sizes indicate their biological and practical relevance remains modest when considered individually.

YSC may serve as a varietal marker, as indicated by IPGRI (International Institute of Plant Genetic Resources IPGRI 1996), since some cultivars present green shoots while others show brownish pigmentation, likely reflecting genetic differences in chlorophyll metabolism. These results align with Calle (2009), who reported high CQ in Geisha accessions with green young shoots at a higher altitude (1500 m a.s.l.). Similarly, coffee varieties such as Bourbon (high PH) and Caturra, Catuaí, and Parainema (low PH), all characterized by green young shoots, have also shown good cup quality (Ferreira et al. 2019; Asociación Nacional del Café ANACAFE Guía de Variedades de Café – Guatemala 2019). Therefore, the association between YSC and CQ is likely explained by the underlying genetic background of the varieties. Most of the *Coffea* accessions that achieved high CQ corresponded to varieties with greater PH, such as Bourbon, Typica, Mundo Novo, Maragogipe, or Geisha, highlighting the role of genotype × environment interactions in quality expression.

These findings reinforce the concept that CQ is determined by genotype × environment interactions, as emphasized by Hameed et al. (2018). At the same time, they illustrate that the simultaneous selection for sensory quality and plant morphological traits remains a challenge, given the limited, context-dependent relationships and small-magnitude effects observed. Nevertheless, our results suggest that agro-morphological traits such as PH and YSC could serve as auxiliary descriptors to complement sensory evaluations during early selection stages, within integrated breeding programs aimed at improving specialty coffee quality.

5 | Conclusions

The contribution of this study was to assess the association between agro-morphological traits and cup quality in Peruvian coffee germplasm across two crop seasons, and to evaluate their predictive capacity using a multivariate modeling approach. The results showed that this association was weak and not consistent, with PH and YSC identified as the only significant predictors, indicating that sensory quality cannot be reliably explained by individual agro-morphological traits. Overall, the evaluated germplasm exhibited high sensory potential, with an average cup quality of 81.56 ± 1.18 points, and most accessions classified as specialty coffee, highlighting its value for specialty coffee production. In this context, agro-morphological traits such as PH and YSC may serve as auxiliary descriptors within integrated selection frameworks to support early-stage germplasm screening and field-level characterization.

Cup quality remained stable across crop seasons, whereas several agro-morphological traits varied between crop seasons. Correlation and PCA analyses revealed weak and inconsistent relationships with cup quality ($r < 0.3$), with a low proportion of explained variance (28.6%), indicating that variation in sensory quality is attributable to multiple interacting factors. Although PH and YSC showed significant effects in the predictive model, these effects were small in magnitude, whereas the remaining traits did not contribute significantly to explaining variation in cup quality, reinforcing the limited predictive capacity of individual agro-morphological traits and highlighting the importance of distinguishing between exploratory associations and robust predictors.

Although the study was based on a limited number of plants per accession and did not include detailed chemical or post-harvest analyses, these aspects highlight the need for further research. Future studies incorporating genomic data, multi-environment trials, and variables related to environmental conditions and post-harvest processing will be essential to better explain variation in cup quality and to strengthen selection strategies in coffee breeding programs.

Author Contributions

Ronald Pio Carrera-Rojo: conceptualization, methodology, formal analysis, validation, investigation, resources, writing – review and editing, and supervision. **José Antonio Ramírez-Peralta:** conceptualization, methodology, formal analysis, investigation, data curation, writing – original draft preparation, writing – review and editing. **José Manuel Cornejo Herrera:** investigation, resources, supervision, writing – review and editing. **José Reategui-Vega:** resources, supervision, writing – review and editing. **Itnan Oscco Medina:** data curation, supervision, writing – review and editing. **Jazmín Yurema Maraví-Loyola:** investigation, resources, supervision, writing – review and editing. **L. David Huayta-Hinojosa:** investigation, formal analysis, visualization, supervision, writing – original draft preparation, writing – review and editing.

Acknowledgements

We thank Ms. Yudi Abad Romaní for her support in data collection; Mr. Sphyros Lastra Paucar, for his guidance and revision of this manuscript; Ms. Savina A. Gutiérrez Calle, for her contribution related to access to genetic resources; and Ms. Jorgelina Brasca for her comments, which significantly improved the manuscript's coherence, clarity, and precision. Finally, we express our sincere gratitude to MSc. Elizabeth Fernandez Huaytalla and Ph.D. Dina L. Gutiérrez Reynoso, for their support in the management of INIA Coffee Germplasm Collection. This research was funded by Instituto Nacional de Innovación Agraria (INIA), within the framework of the Project CUI N° 2480490 "Mejoramiento de los Servicios de Investigación en la Caracterización de los Recursos Genéticos de la Agrobiodiversidad en 17 Departamentos del Perú (ProAgrobio)".

Ethics Statement

It is hereby reported that, for the present research, the species *Coffea arabica* is exempt from the procedure of access to genetic resources and their derivatives in Peru, since it is an introduced species, in accordance with Article 3 of Decision No. 391 – Common Regime on Access to Genetic Resources, Andean Community (https://www.gob.pe/institucion/inia/informes-publicaciones/4167896-decision-n-391-regimen-comun-sobre-acceso-a-los-recursos-geneticos). Furthermore, coffee cultivation is not of Peruvian origin, therefore, obtaining and using the genetic material of the aforementioned species, from the INIA Germplasm Bank, is outside the scope of the Regulation on Access to Genetic Resources, as established in Article 4 of such regulation, for this reason, it does not need to manage access to genetic resources and/or their derivatives (Decreto Supremo No. 019-2021-MINAM, https://www.gob.pe/institucion/inia/informes-publicaciones/4167935-decreto-supremo-n-019-2021-minam).

Likewise, the INIA Coffee Germplasm Collection is managed by the Genetic Resources Sub-Directorate – SDRG of the Genetic Resources and Biotechnology Directorate – DRGB of INIA; which is responsible for carrying out the development of conservation and characterization activities of genetic resources in ex situ conditions, with the aim of valuing the genetic resources of agrobiodiversity and promoting their sustainable use. (Article 60 - Resolución Jefatural N° 0006-2025-INIA, https://www.gob.pe/institucion/inia/normas-legales/6371876-0006-2025-inia).

Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

Data sets generated and/or analyzed in the present work are not publicly available in response to INIA policies, which require confidentiality. They may be made available upon reasonable request to the corresponding author.

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