MORPHOLOGICAL DIVERSITY OF *Coffea arabica* L. WITH YELLOW, ORANGE, AND PURPLE FRUIT FROM TEMANGGUNG

KERAGAMAN MORFOLOGI *Coffea arabica* L. DENGAN WARNA BUAH KUNING, ORANYE, DAN UNGU DARI TEMANGGUNG

Aswin Hendry Atmoko [1], Sri Hartati [2*], Parjanto [2]

[1] Department of Agronomy, Faculty of Agriculture, Universitas Sebelas Maret, Jl.Ir. Sutami No. 36A, Jebres, Jebres District, Surakarta City 57126, Central Java, Indonesia
[2] Department of Agrotechnology, Faculty of Agriculture, Universitas Sebelas Maret, Jl.Ir. Sutami No. 36A, Jebres, Jebres District, Surakarta City 57126, Central Java, Indonesia

Correspondence: srihartati57@staff.uns.ac.id

Accepted: 08th April 2026/ Revised: 19th May 2026 / Approved: 30th July 2026

ABSTRACT

Temanggung possesses unique Arabica coffee accessions with yellow, orange, and purple ripe fruits. However, their morphological diversity has not yet been documented using standardized IPGRI descriptors. This study evaluated the morphological diversity of 15 *Coffea arabica* accessions with distinct fruit color using 29 qualitative morphological characters. The results revealed substantial variation among accessions, Shannon–Wiener diversity index (H') ranging from 0.000 to 1.679, with an average of 0.721, suggesting overall moderate diversity. Highly variable traits included young leaf color, shoot color, fruit color, fruit shape, and seed shape. While characters such as venation pattern, bud wax color, domatia shape, and inflorescence position were uniform across accessions. Fruit color, the primary distinguishing trait, exhibited high diversity (H' = 1.552), comprising six distinct categories, with orange being the most dominant. Fruit color showed substantial variation, but no consistent morphological pattern was observed across accessions with different fruit colors. Further genetic and association analyses are needed to clarify the relationship between fruit color and other qualitative traits. Cluster analysis using the Unweighted Pair Group Method with Arithmetic Mean (UPGMA) implemented in NTSYSpc version 2.02i grouped the accessions into two major clusters, with one accession forming a distinct cluster, reflecting its unique morphological characteristics. The similarity index ranged from 0.27 to 0.75, indicating moderate to high diversity and the absence of closely identical accessions based on morphological traits. These findings confirm that observed Arabica coffee accessions from Temanggung possess considerable morphological variability, providing a valuable genetic resource for selection and breeding programs.

Key words: Arabica coffee, germplasm, local, morphological variation, phenotype

ABSTRAK

Temanggung memiliki aksesi kopi Arabika yang unik dengan buah matang berwarna kuning, oranye, dan ungu. Namun keragaman morfologinya belum didokumentasikan dengan menggunakan deskriptor berstandar IPGRI. Penelitian ini bertujuan untuk mengevaluasi keragaman morfologi 15 aksesi *Coffea arabica* dengan warna buah yang berbeda menggunakan

ISSN: 2407-7933

Cite this as: Atmoko, A. H., Hartati, S. & Parjanto. (2026). Morphological diversity of *Coffea arabica* L. with yellow, orange, and purple fruit from Temanggung. *Jurnal Agro*, *13*(1), 99-116. https://doi.org/10.15575/j.agro.55184

29 karakter morfologi kualitatif. Hasil penelitian menunjukkan variasi morfologi yang cukup besar antar aksesi, dengan indeks keragaman Shannon–Wiener (H’) berkisar antara 0.000–1.679 dan rata-rata 0.721, yang menunjukkan tingkat keragaman sedang. Karakter dengan keragaman tinggi meliputi warna daun muda, warna tunas, warna buah, bentuk buah, dan bentuk biji. Sedangkan, pola venasi daun, warna wax kuncup, bentuk domatia, dan posisi bunga menunjukkan kondisi yang seragam pada seluruh aksesi. Warna buah sebagai karakter pembeda utama memiliki keragaman tinggi (H’ = 1.552) dengan enam kategori warna, didominasi oleh warna oranye. Meskipun demikian, tidak ditemukan pola morfologi yang konsisten pada aksesi dengan warna buah yang berbeda. Oleh karena itu, analisis genetik dan analisis asosiasi masih diperlukan untuk mengklarifikasi hubungan antara warna buah dan karakter morfologi kualitatif lainnya. Analisis klaster menggunakan metode Unweighted Pair Group Method with Arithmetic Mean (UPGMA) dengan aplikasi NTSYSpc versi 2.02i mengelompokkan aksesi menjadi dua klaster besar, dengan satu aksesi membentuk cluster yang berbeda, mencerminkan karakteristik morfologi yang unik. Indeks kemiripan berkisar antara 0.27–0.75, menunjukkan keragaman morfologi sedang hingga tinggi tanpa adanya aksesi yang identik. Temuan ini menegaskan bahwa aksesi kopi Arabika Temanggung memiliki keragaman morfologi yang tinggi dan berpotensi menjadi sumber daya genetik yang penting untuk program seleksi dan pemuliaan.

Kata kunci: Fenotip, kopi Arabika, lokal, plasma nutfah, variasi morfologi

INTRODUCTION

Arabica coffee (*Coffea arabica* L.) is an important plantation crop species originating from the *Rubiaceae* family which is thought to originate from natural hybridization between *Coffea canephora* x *Coffea eugenioides* (Salojärvi et al., 2024). Karyotypically, Arabica coffee is an allotetraploid organism with a chromosome profile of 2n = 4x = 44 (Geleta et al., 2012), although both original parents have diploid (2n) chromosomes. Arabica coffee is a self-pollinating plant (autogamous); this condition has an effect on the small amount of genetic variation produced by Arabica coffee naturally (Campuzano-Duque & Blair, 2022), posing challenges for breeding and genetic improvement. However, genetic variation remains essential for germplasm conservation, cultivar development, and adaptation to environmental changes. Although self-pollinating plants generally exhibit limited genetic variability, greatest possibility of genetic variation can arise through spontaneous mutations, occasional outcrossing, meiotic recombination, and segregation, while environmental factors mainly influence phenotypic expression (Busch et al., 2022).

Despite its limitations, Arabica coffee has many benefits, including as a specialty coffee beverage that is widespread and popular in various countries (Abdelwahab et al., 2024). Arabica coffee also has health benefits, because it contains beneficial compounds such as Kahweol, Cafestol, Caffeine, Trigonelline, and Chlorogenic acid which are useful as antioxidants, anti-inflammatories, nerve health, and even recreational functions (Kobylińska et al., 2025), so that utilization and development become important.

Indonesia, particularly Temanggung Regency, Central Java, is a major Arabica coffee-producing region in Indonesia, especially for the export market (Ashardiono & Trihartono, 2024), producing coffee of distinctive quality from the highlands of Mount Sindoro (3,153 m) and Mount Sumbing (3,371 m), including a tobacco-like aftertaste attributed to intercropping with tobacco. However, Robusta production substantially exceeds Arabica in Temanggung (8,368.96 tons versus 626.09 tons in 2024) (BPS Kabupaten Temanggung, 2025), resulting in a research focus skewed toward Robusta despite the higher market value and export demand for Arabica (Mendes et al., 2024)

Phenotypic variation in local Arabica coffee constitutes a critical basis for crop improvement, beginning with morphological characterization using qualitative traits to assess diversity and identify potential genotypes (Malek et al., 2014). Qualitative traits, being controlled by few major genes and minimally influenced by environmental factors, provide reliable information for distinguishing accessions (Yirgu et al., 2022). This study therefore applied standardized IPGRI descriptors to ensure consistency and comparability with other coffee germplasm studies, although confirmation of genotypic differences ultimately requires molecular analysis..

Fruit color represents a key morphological marker of economic importance in coffee. While ripe coffee cherries are typically red (Osorio Pérez et al., 2023), mutations can alter this color to yellow, as observed in the Yellow Bourbon cultivar from Brazil (Romano et al., 2022), resulting from a double-recessive Xanthocarpa gene that inhibits red pigment accumulation (Hu et al., 2022) without altering the overall genome, instead affecting the pigment biosynthesis pathway in the fruit skin (Zhang et al., 2024). However, the relationship between fruit color variation and qualitative morphological traits, as well as its link to genotypic differentiation, remains poorly understood.

Preliminary field exploration by the research team in major Arabica-growing areas of Temanggung identified local accessions with yellow, orange, and purple ripe fruits that have not yet been systematically characterized using standardized IPGRI descriptors. The association between fruit color and qualitative morphological traits remains unclear, limiting the utilization of local germplasm for breeding and conservation. This study therefore aims to characterize the morphological variation of Coffea arabica accessions with differing fruit colors, hypothesizing that yellow-, orange-, and purple-fruited accessions exhibit significant morphological differences reflecting underlying phenotypic diversity.

MATERIALS AND METHODS

Time and Location of Research

Exploration and characterization were carried out from August 2025 to January 2026. Fifteen coffee accessions were found and directly observed at the origin locations of the accessions in five sub-districts in Temanggung Regency, namely Tlogomulyo (TGL), Candiroto (CDR), Ngadirejo (NGD), Bansari (BNS), and Bejen (BJN). The plantation/land used was owned by local farmers and also several coffee agroforestry managed by LMDH (Lembaga Masyarakat Desa Hutan).

Tools and Materials

The tools used in this study include a ruler, arc ruler, tweezers, razor blade, magnifying glass, GPS, altimeter, digital camera with a macro lens, and morphological descriptor book published by IPGRI (International Plant Genetic Resources Institute for *Coffee* spp., 1996). A total of 15 Arabica coffee accessions bearing non-red ripe fruits were identified during the preliminary field exploration and included in this study. These accessions represent the entire population of non-red fruit accessions encountered during the survey. Each accession corresponded to a single individual plant identified in the field. The accessions comprised Arabica coffee plants bearing yellow, orange, purple, or other non-red ripe fruits and were identified through a preliminary field survey conducted in coffee plantations. The limited number of accessions reflects the rarity of naturally occurring non-red ripe fruit phenotypes in the surveyed Arabica coffee populations. Details and origin of accessions can be seen in Table 1.

Table 1. Information and detail on observed coffee accessions

Accession Code	Known Origin	Location Coordinates	Altitude (masl)
1-P.Violet-BJN	Identified in red population	7°10'03.90"S 110°01'51.88"E	1073
2-P.Violet-BJN	Identified in red population	7°10'14.06"S 110°01'50.35"E	1086
3-Orange-TGL	Yet unknown	7°21'31.01"S 110°06'03.91"E	1550
4-Yellow-TGL	Introduction*	7°21'46.73"S 110°06'36.01"E	1439
5-Orange-CDR	Introduction*	7°15'27.80"S 110°00'28.94"E	1458
6-Purple-CDR	Yet unknown	7°15'19.60"S 110°00'34.26"E	1395
7-Orange-CDR	Yet unknown	7°15'20.15"S 110°00'28.58"E	1397
8-Orange-CDR	Identified in red population	7°16'24.65"S 110°00'08.75"E	1783
9-Orange-NGD	Yet unknown	7°15'37.48"S 110°00'41.89"E	1409
10-Orange-NGD	Introduction*	7°15'50.82"S 110°00'36.64"E	1490
11-Orange-BNS	Grows not on coffee plantation	7°17'26.75"S 110°01'09.00"E	1783
12-P.Violet-BNS	Yet unknown, self-seeding	7°17'21.64"S 110°01'35.32"E	1593
13-Orange-BNS	Yet unknown	7°18'00.02"S 110°01'43.22"E	1586
14-Violet-BNS	Seed from the parents (red)	7°17'20.04"S 110°01'34.43"E	1593
15-Orange-BNS	Grows not on coffee plantation	7°17'21.64"S 110°02'10.09"E	1383

Explanation: BJN: Bejen, TGL: Tlogomulyo, CDR: Candiroto, NGD: Ngadirejo, BNS: Bansari. The meaning of the accession code is: accession number-ripe fruit color-sub-district abbreviation. *: Historical origin was obtained from farmer interviews and field records. Some parent plants were reportedly introduced from outside Temanggung as red-fruited Arabica coffee, whereas the non-red fruit phenotype was observed only after long-term cultivation or subsequent seed propagation under local conditions.

Research Method

This research is an exploratory descriptive study that focuses on the findings of Arabica coffee accessions with uncommon ripe fruit colors (yellow, orange, and purple) and provides descriptive information of the qualitative morphological characteristics of each accession. The research was conducted by directly observing qualitative morphological characters and documenting each group of characters obtained. Following the UPOV (2008) guidelines, morphological characterization was conducted on 15 Arabica coffee accessions, each represented by a single plant grown from seed. For each qualitative character, observations were made on 20 randomly selected organs (e.g., leaves, flowers, fruits, or seeds, depending on the character assessed) from the same plant. These observations served as subsamples to improve the reliability of character assessment and were not considered biological replicates.

Table 2. Morphological characters and scoring

Plant Part	No.	Character	Scoring
Vegetative	1.	Appearance	[1] Elongated Conical, [2] Pyramidal, and [3] Bushy
	2.	Development	[1] Monopodial and [2] Sympodial
	3.	Primary Branch Angle Insertion	[1] Drooping, [2] Horizontal or Spreading, and [3] Semi-Erect
	4.	Stipule Shape	[1] Round, [2] Ovate, [3] Triangular, [4] Deltate, [5] Trapeziform, [6] Splited, and [7] Others
	5.	Young Leaf Color	[1] Greenish, [2] Green, [3] Brownish, [4] Reddish Brown, [5] Bronze, [6] Purple, [7] Yellow, [8] Orange, and [9] Others
	6.	Leaf Shape	[1] Obovate, [2] Ovate, [3] Elliptic, [4] Lanceolate, [5] Undulate, and [6] Others
	7.	Leaf Apex Shape	[1] Round, [2] Obtuse, [3] Acute, [4] Acuminate, [5] Apiculate, [6] Spatulate, and [7] Others
	8.	Leaf Petiole Color	[1] Green, [2] Dark Brown, [3] Purple, and [4] Others
	9.	Shoot Color	[1] Light Green, [2] Green, [3] Dark Green, [4] Yellow, [5] Orange, [6] Brown, [7] Dark Brown, [8] Light Purple, [9] Dark Purple, and [10] Others
	10.	Mature Leaf Color	[1] Light Green, [2] Green, [3] Dark Green, [4] Yellowish Green, [5] Yellow, [6] Purple, and [7] Others
	11.	Venation Pattern	[1] Arcuate, [2] Cross-Venulate, [3] Pinnate, [4] Reticulate, and [5] Others
	12.	Bud Wax Color	[0] Absent, [1] Clear Shiny, [2] Yellowish, and [3] Others
	13.	Domatia Pilosity	[1] Seldom, [2] Intermediate, and [3] Congested
	14.	Shape of Domatia	[1] Pocket, [2] Tuft, [3] Tuft-Pocket, [4] Pit-Type, and [5] Others
	15.	Domatia Position	[1] Axillary and [2] Extra-Axillary
Generative	16.	Inflorescence Position	[1] Axillary and [2] Terminal
	17.	Inflorescence in Old Wood	[0] Absent and [1] Present
	18.	Anther Insertion	[1] Excluded and [2] Included
	19.	Stigma Position Toward Anther	[1] Excluded, [2] Parallel, and [3] Included
	20.	Flower Petal Color	[1] White and [2] Yellowish White
	21.	Corolla Tube Color	[1] White, [2] Yellow, and [3] Pink
	22.	Fruit Color	[1] Yellow, [2] Semi-Orange Yellow, [3] Orange, [4] Reddish Orange, [5] Red, [6] Purplish Red, [7] Purple, [8] Purple Violet, [9] Violet, [10] Black, and [11] Others
	23.	Fruit Shape	[1] Roundish, [2] Obovate, [3] Ovate, [4] Elliptic, [5] Oblong, [6] Upside Down Heart, [7] Others
	24.	Fruit Ribs	[0] Absent and [1] Present
	25.	Endocarp Texture	[1] Coriaceous, [2] Sub-Coriaceous, and [3] Others
	26.	Fruit Disc Shape	[1] Not Marked, [2] Marked but Not Prominent, [3] Prominent (Cylindrical), and [4] Beaked
	27.	Calyx Limb Persistance	[0] Absent and [1] Present
	28.	Seed Color	[1] Yellow, [2] Brownish Yellow, [3] Orange, [4] Brown, [5] Purplish Brown, and [6] Others
	29.	Seed Shape	[1] Round, [2] Obovate, [3] Ovate, [4] Elliptic, [5] Oblong, and [6] Others

Morphological characterization consists of 29 morphological characters that are adapted to the descriptor book by International Plant Genetic Resources Institute or IPGRI (1996) for *Coffea* spp., consisting of stem, leaf, flower, fruit and seed characteristics. The morphological characters obtained from the observed plants will then be converted into a numerical scoring (e.g., 1, 2, 3, 4, and so on) to indicate the differences in each character group. When variation occurred among the observed organs within an accession, the most frequently occurring character was recorded as the representative score, following the UPOV descriptor guidelines. The observed morphological characters and scoring information can be seen in Table 2

Research Stages

The study began with a survey and exploration of coffee accessions across major Arabica production centers in Temanggung, combining purposive, exploratory, and key informant survey methods to gather information from farmers. Field surveys targeted plantations above 1,000 masl known to harbor Arabica coffee with unusual ripe fruit colors, covering eight sub-districts in total. No non-red fruited accessions were found in Kledung, Bulu, or Parakan. Overall, the survey encompassed 31 plantations across 15 villages, comprising 24 farmer-owned plantations and seven managed by the Forest Village Community Institution (LMDH).

Surveys were conducted during August–September, coinciding with the harvest (generative) season in Temanggung, to facilitate observation and data collection of accessions with non-red ripe fruit colors. Verification of Arabica coffee accessions involved three approaches: (1) direct information from farmers, (2) examination of cultivation origin, species identity, and official cultivar description tables/vouchers where available, and (3) preliminary morphological observations to differentiate coffee species. Collected accessions were labeled with passport codes following the format accession number–ripe fruit color–sub-district abbreviation, and each was subsequently evaluated based on predetermined qualitative morphological traits.

Analysis Method

Data analysis involved converting observed morphological characters into nominal (multi-state) scores to enhance grouping accuracy across traits. Invariant qualitative characters were excluded prior to cluster analysis, as they did not contribute to discrimination among accessions; only polymorphic characters were used to construct the similarity matrix and perform clustering. A similarity matrix was generated from the qualitative data using the Simple Matching (SM) coefficient via the SIMQUAL procedure, then subjected to hierarchical cluster analysis using the Unweighted Pair Group Method with Arithmetic Mean (UPGMA) to construct a phenogram based on average linkage among accessions. Goodness-of-fit of the UPGMA phenogram was evaluated using the cophenetic correlation coefficient (CCC), measuring agreement between the original similarity matrix and the cophenetic matrix derived from the dendrogram. Cluster analysis was performed using NTSYSpc, series 2.02i (Rohlf, 1992).

Phenotypic diversity was assessed based on the frequency and distribution of each qualitative character category using the Shannon–Wiener diversity index (H'), which also identifies low-variability (homogeneous) characters of limited selective value versus high-variability (diverse) characters contributing most to overall variation and thus holding greater breeding potential. The Shannon Diversity Index formula is:

$$\mathrm{H}' = -\sum_{i=1}^{S} Pi\ \ln(pi)$$

where Pi is the proportion of accessions in a given character category, Ni is the number of accessions per category (or observed individuals/organs), ln is the natural logarithm, and ln Pi weights the informational value of each character category. Based on H' values, diversity is classified as low (H' < 0.5), medium (0.5 ≤ H' ≤ 0.75), or high (H' > 0.75) (Azam et al., 2023; Maxiselly et al., 2025).

RESULTS AND DISCUSSION

Morphological Variation Based on Qualitative Traits

Plant characterization based on morphology is an initial activity for germplasm conservation and accession selection with the aim of differentiating between genotype as well as for practical purposes in the form of selection for plant breeding. Collecting coffee plants of the same species but having genotypic variations is an important thing in the initial process of plant breeding, because in this way, breeders can obtain parental candidates that genetically possess many choices of profitable traits, both agronomically and for other developments. Therefore the morphological variations seen in Arabica coffee accessions become very valuable initial information/database.

In the context of genetics, qualitative traits are phenotypic characteristics that occur as discrete categories rather than continuous measurements. Compared with quantitative traits, qualitative traits are generally less influenced by environmental conditions and often have a stronger genetic basis (Jing et al., 2025). Many qualitative traits, such as color and shape, are predominantly controlled by one or a few major genes, although the genetic architecture may vary among traits and species. Consequently, differences in qualitative morphological traits can provide useful information for distinguishing accessions and may indicate underlying genetic variation (Andini et al., 2025). However, these traits alone are insufficient to confirm genotypic differences, which require validation using molecular or other genetic analyses. 15 Arabica coffee accessions obtained were analyzed using the Shannon-Wiener diversity index using 29 qualitative characters (Table 3), showing varying frequencies for each observed character, evidenced by the varying H' index categories ranging from none, low, medium, to high.

The observed variation in qualitative morphological characters among the 15 Arabica coffee accessions with yellow, orange, and purple fruit colors provides preliminary evidence of phenotypic differentiation among accessions. Thus, accessions exhibiting unique phenotypic characteristics can be prioritized for subsequent molecular characterization to verify their underlying genetic variation. Each existing variation is important information for identification and selection (Govindaraj et al., 2015). Based on H', the index range is the lowest at 0.000, which means there is no variation at all, to the highest index of 1.679, which means a very high variation in morphological characters, indicating the presence of morphological characters that do not vary at all, such as venation patterns, bud wax color, domatia shape, domatia position, and inflorescence position, as well as very diverse morphological characters such as young leaf color, young shoot color, fruit color, and fruit shape. The average H' index for 29 characters is 0.721, which means that overall it is classified as a moderate/medium diversity category. Overall, there are 12 characters in the high category, 9 characters in the medium category, 2 characters in the low category, and 6 characters with no diversity.

Table 3. Diversity of morphological characters and Shannon-Wiener index (H')

Plant Part	Character	Sub-Character	N	H’	Criteria
Vegetative	Appearance	[1] Elongated conical	1	0.892	High
		[2] Pyramidal	7		
		[3] Bushy	7		
	Development	[1] Monopodial	6	0.673	Medium
		[2] Sympodial	9		
	Primary branch angle insertion	[2] Horizontal or spreading	3	0.500	Medium
		[3] Semi-erect	12		
	Stipule shape	[2] Ovate	2	1.245	High
		[3] Triangular	7		
		[4] Deltate	4		
		[5] Trapeziform	2		
	Young leaf color	[1] Greenish	7	1.338	High
		[3] Brownish	4		
		[5] Bronze	2		
		[6] Purple	1		
		[8] Orange	1		
	Leaf shape	[2] Ovate	4	1.010	High
		[3] Elliptic	8		
		[4] Lanceolate	3		
	Leaf apex shape	[3] Acute	4	1.010	High
		[4] Acuminate	8		
		[5] Apiculate	3		
	Leaf petiole color	[1] Green	14	0.245	Low
		[3] Purple	1		
	shoot color	[1] Light green	1	1.679	High
		[2] Green	6		
		[3] Dark green	2		
		[4] Yellow	3		
		[6] Brown	1		
		[7] Dark brown	1		
		[9] Dark purple	1		
	Mature leaf color	[2] Green	2	0.628	Medium
		[3] Dark green	12		
		[6] Purple	1		
	Venation pattern	[3] Pinnate	15	0.000	None
	Bud wax color	[1] Clear shiny	15	0.000	None
	Domatia pillosity	[1] Seldom	5	1.085	High
		[2] Intermediate	6		
		[3] Congested	4		
	Shape of domatia	[4] Pit-type	15	0.000	None
	Domatia position	[1] Axillary	15	0.000	None
Generative	Inflorescence position	[1] Axillary	15	0.000	None
	Inflorescence in old wood	[0] Absent	8	0.691	Medium

	[1] Present	7		
Anther insertion	[1] Excluded	15	0.000	None
Stigma position toward anther	[1] Excluded [2] Parallel [3] Included	9 5 1	0.853	High
Flower petal color	[1] White [2] Yellowish-white	14 1	0.245	Low
Corolla tube color	[1] White [2] Yellow [3] Pink	11 3 1	0.730	Medium
Fruit color	[1] Yellow [2] Semi-orange yellow [3] Orange [7] Purple [8] Purple violet [9] Violet	1 3 6 1 3 1	1.552	High
Fruit shape	[1] Roundish [2] Obovate [4] Elliptic [5] Oblong	9 2 3 1	1.078	High
Fruit ribs	[0] Absent [1] Present	6 9	0.673	Medium
Endocarp texture	[1] Coriaceous [2] Sub-coriaceous	12 3	0.500	Medium
Fruit disc shape	[1] Not marked [2] Marked but not prominent [3] Prominent (cylindrical) [4] Beaked	2 4 5 4	1.340	High
Calyx limb persistance	[0] Absent [1] Present	8 7	0.691	Medium
Seed color	[1] Yellow [3] Orange [4] Brown	11 3 1	0.730	Medium
Seed shape	[1] Round [2] Obovate [3] Ovate [4] Elliptic [5] Oblong	1 6 3 3 2	1.459	High

Explanation: N: Number of sub-morphological characters found in accessions, H’: Shannon-Wiener index, and sub-morphological characters that not listed in the table are characters that were not found in the observed accessions.

One of the morphological characters that was focused on, or became a marker of accession in this study, namely fruit color, showed a relatively high H' value of 1.552, with 1 accession being yellow, 3 accessions being semi-orange yellow, 6 accessions being orange, 1 accession being purple, 3 accessions being purple violet, and 1 accession being violet. Fruit color is a qualitative trait (Huang & Hsieh, 2017). Based on previous research studies, Genes influencing fruit color may function as regulators of gene expression, particularly in metabolic pathways responsible for pigment accumulation in the fruit skin, and fruit color is often determined by one or a few major genes acting synergistically (Gonzali & Perata, 2021). Therefore, variation in fruit color may reflect underlying genetic variation (Shu et al., 2023). This result suggests that there is no specific pattern of other characters that depend on the color of the coffee fruit. Thus, the color characteristics of coffee cherries can generally be used as an initial indication to differentiate coffee plant accessions.

No consistent morphological pattern was observed among accessions with different fruit colors, indicating that fruit color variation was not accompanied by obvious differences in the qualitative morphological traits evaluated (Li et al., 2018). This is consistent with the concept that pigment-related genes often regulate specific metabolic pathways without significantly affecting other phenotypic characters. Several qualitative morphological characters, including leaf venation pattern, bud wax color, domatia shape, and inflorescence position, showed no variation among the 15 Arabica coffee accessions. The uniformity of these traits suggests that they are highly conserved within the evaluated germplasm and therefore contribute little to distinguishing accessions. In contrast, variation observed in other qualitative traits reflects phenotypic diversity among accessions. The origin of this variation was not investigated in the present study and may be associated with multiple evolutionary or breeding processes, including mutation, recombination, occasional outcrossing, or the introduction of genetically distinct planting materials.

Cluster Analysis Based on Qualitative Morphology

Based on observations and information obtained, the 15 accessions observed came from different sources. Based on information obtained from farmers, a small parent plants had originally been introduced from outside Temanggung as red-fruited Arabica coffee. The non-red fruit phenotypes were reported to have appeared only after long-term cultivation in Temanggung or in subsequent generations propagated by seed. However, the mechanisms underlying these phenotypic changes were not investigated in the present study. Most of the accessions were identified only after reaching the fruiting stage within predominantly red-fruited Arabica coffee populations, whereas others originated from seed propagation of Arabica coffee plants that did not exhibit non-red ripe fruits. Several biological processes may explain the observed phenotypic variation, including spontaneous mutation, meiotic recombination during sexual reproduction, occasional outcrossing, or the introduction of genetically distinct planting materials. Although Coffea arabica is predominantly self-pollinating, natural cross-pollination has been reported to occur at relatively low frequencies (approximately 4–10%) (Unigarro et al., 2025), which may also contribute to morphological variation.

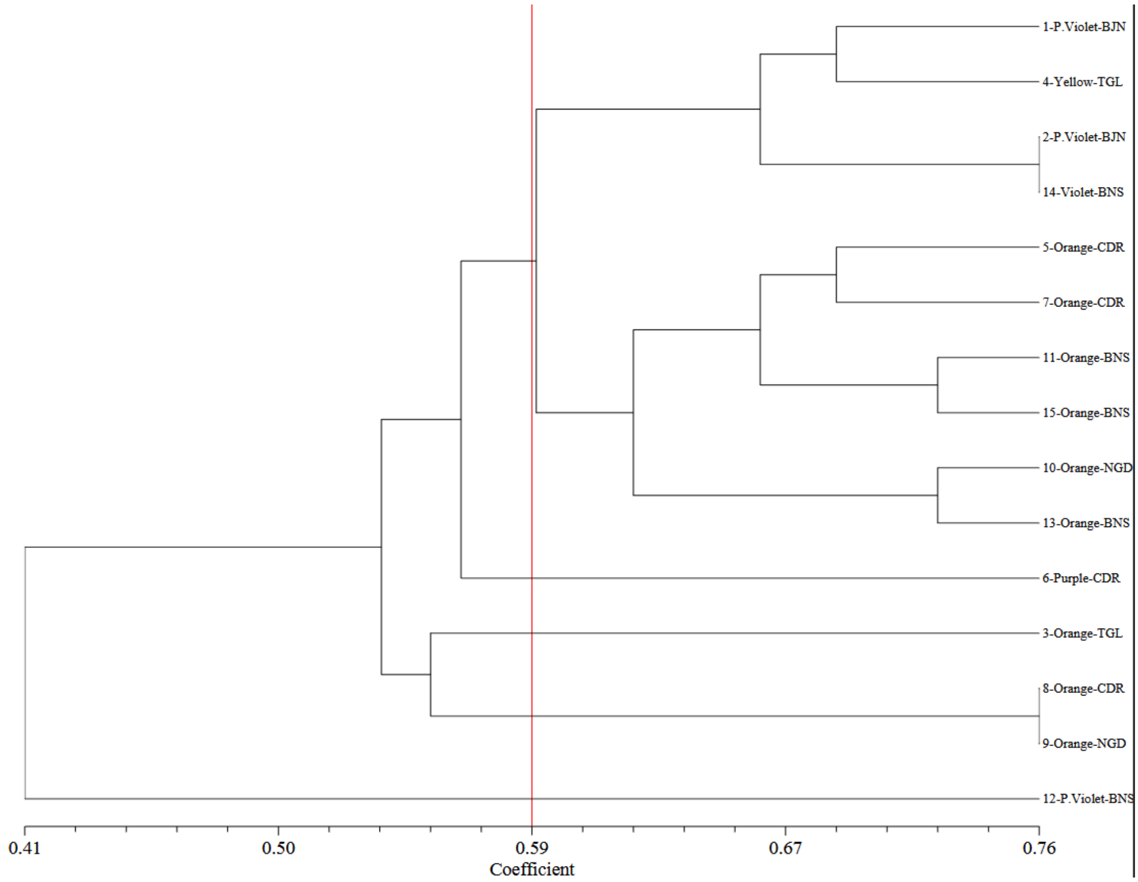

Figure 1. Phenogram of 15 Arabica coffee accessions

Cluster analysis is needed to determine the similarities and differences between each accession. From the similarity analysis, it can also be understood how closely related one accession is to another accession. Cluster analysis can also show patterns between accessions based on morphological characteristics. Several accessions with high/close morphological similarities will be grouped into the same cluster or even sub-cluster, and accessions with distant similarities will be grouped into different clusters. Based on the phenogram formed (Figure 1), it can be understood that there are 2 large clusters, where cluster 1 consists of 14 accessions, while cluster 2 only contains 1 accession, namely 12-P.Violet-BNS, while the rest are included in cluster 1. Indicates that accession 12-P.Violet-BNS has the most distinct qualitative morphological characters. 5 sub-groups/sub-clusters were formed based on similarity, namely sub-cluster 1 consisting of 1-P.Violet-BJN, 4-Yellow-TGL, 2.P.Violet-BJN and 14-Violet-BNS. subcluster 2 consisting of 5-Orange-CDR, 7-Orange-CDR, 11-Orange-BNS, and 5-Orange-BNS. subcluster 3 consisting of 10-Orange-NGD and 13-Orange-BNS. sub-cluster 4 only consisting of accession 6-Purple-CDR. sub-cluster 5 consisting of 3-Orange-TGL, 8-Orange-CDR, and 9-Orange-NGD.

The phenogram formed shows that each accession shows moderate to high morphological diversity, when expressed in an index, the similarity between accessions (when each is compared) can be observed in the similarity matrix table (Table 4). The similarity range is only between 0.27 - 0.75 so that the existing diversity is quite significant, indicating that there are no accessions with a similarity of more than 0.75 or none that are exactly the same. An example of an accession with a very low similarity of 0.27 is between accessions 6-Purple-CDR and 12-P.Violet-BNS. while examples of accessions with a high similarity of 0.75 are between 2-P.VioletBJN and 14-Violet-BNS also 8-Orange-CDR and 9-Orange-NGD. The lowest index of 0.27 indicates the highest divergent/diversity, while the highest index of 0.75 indicates the maximum similarity index, which shows the most similar accessions. The UPGMA phenogrm showed a cophenetic correlation coefficient (CCC) of 0.796, indicating an acceptable agreement (Mohammadi & Prasanna, 2003) between the original similarity matrix and the clustering structure represented by the dendrogram. The cluster analysis shows that the diversity of coffee accessions that have yellow, orange, and purple fruit colors is quite high because the similarity index value is quite low at 0.27 (Hopkins & Gerber, 2017).

Table 4. Similarity matrix of 15 Arabica coffee accessions

Acc.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1	1.00														
2	0.62	1.00													
3	0.48	0.48	1.00												
4	0.68	0.65	0.41	1.00											
5	0.62	0.48	0.48	0.62	1.00										
6	0.58	0.41	0.48	0.55	0.58	1.00									
7	0.65	0.62	0.58	0.58	0.68	0.68	1.00								
8	0.51	0.58	0.51	0.48	0.65	0.44	0.65	1.00							
9	0.34	0.55	0.58	0.41	0.58	0.37	0.48	0.75	1.00						
10	0.48	0.55	0.58	0.55	0.58	0.58	0.55	0.65	0.58	1.00					
11	0.51	0.62	0.65	0.55	0.62	0.48	0.65	0.58	0.51	0.62	1.00				
12	0.34	0.48	0.48	0.31	0.31	0.27	0.31	0.44	0.55	0.44	0.58	1.00			
13	0.62	0.62	0.55	0.65	0.62	0.58	0.68	0.62	0.48	0.72	0.62	0.44	1.00		
14	0.68	0.75	0.48	0.68	0.58	0.58	0.72	0.62	0.48	0.62	0.55	0.37	0.65	1.00	
15	0.55	0.55	0.58	0.55	0.68	0.55	0.68	0.65	0.55	0.62	0.72	0.41	0.65	0.55	1.00

Explanation: Acc: Accession, 1: 1-P.Violet-BJN, 2: 2-P.Violet-BJN, 3: 3-Orange-TGL, 4: 4-Yellow-TGL, 5: 5-Orange-CDR, 6: 6-Purple-CDR, 7: 7-Orange-CDR, 8: 8-Orange-CDR, 9: 9-Orange-NGD, 10: 10-Orange-NGD, 11: 11-Orange-BNS, 12: 12-P.Violet-BNS, 13: 13-Orange-BNS, 14: 14-Violet-BNS, and 15: 15-Orange-BNS.

Implications for Plant Breeding Based on Biodiversity

Variations in the qualitative morphology of plants are an indication of genotypic diversity (Yeshitila et al., 2024) and biodiversity in plant species is a profitable resource for plant breeding programs (Salgotra & Chauhan, 2023). This is a solution to the genetic limitations of Arabica coffee to produce variations naturally, because of its autogamous reproductive system, so that human intervention is needed, especially in plant breeding to obtain Arabica coffee cultivars with more profitable and adaptive traits. Based on the similarity index obtained, it can be understood that the 15 Arabica coffee accessions obtained show differences from each other so that they are potential candidates for further evaluation in breeding programs. Moreover, the accessions obtained, although they show variations, but are in the same species, generally compatible for crossing (Tounekti et al., 2017). However, the selection of parental combinations should be carefully considered. Crosses between parents with relatively similar morphological characteristics may be advantageous for maintaining desirable traits and may be associated with higher compatibility, whereas crosses involving more morphologically divergent parents may provide greater opportunities to generate phenotypic variation in the progeny. Nevertheless, the relationship between morphological divergence, cross compatibility, and progeny variation should be interpreted with caution, as these aspects are influenced by multiple genetic and biological factors (JM et al., 2015; Atmoko et al., 2026).

15 coffee accessions exhibited quite diverse qualitative morphological character variations, such as fruit color, young leaf color, and stigma position towards anther (Figure 2). The ripe color of the fruit in Arabica coffee apparently influences the beneficial agronomic properties, Previous studies have shown that yellow color is able to produce higher sugar content than other colors (Hernández-Alcántara et al., 2023). The sugar content in the coffee fruit/cherry will be able to influence the taste of the coffee, sugar content influences flavor indirectly by acting as a precursor in Maillard reactions during roasting, leading to the formation of key aroma and taste compounds that determine coffee quality especially those processed using natural (dried with fruit skin) processes (Baptistella et al., 2024). Although sugar content and sensory quality were not evaluated in the present study, variation in fruit color may have potential implications for future research especially on the sensory quality of coffee.

The high qualitative morphological diversity of *Coffea arabica* is an important component in plant breeding programs. Qualitative traits are generally controlled by one or a few key genes, thus serving as relatively useful preliminary descriptors for accession differentiation. The presence of morphological variations, such as differences in fruit color, leaf characteristics, and plant architecture, is predicted reflects differences in genotypes that can be utilized in selection and crossing processes. High diversity increases the opportunity to identify superior accessions with desired traits, while broadening the genetic base for breeding programs. Furthermore, the use of genetically diverse parents has the potential to produce segregant populations with a wider range of phenotypes, increasing the likelihood of obtaining new superior varieties. Therefore, the morphological diversity observed in Arabica coffee germplasm represents a valuable resource for breeding, conservation, and the development of varieties that are adapted to diverse environmental conditions and meet market demands.

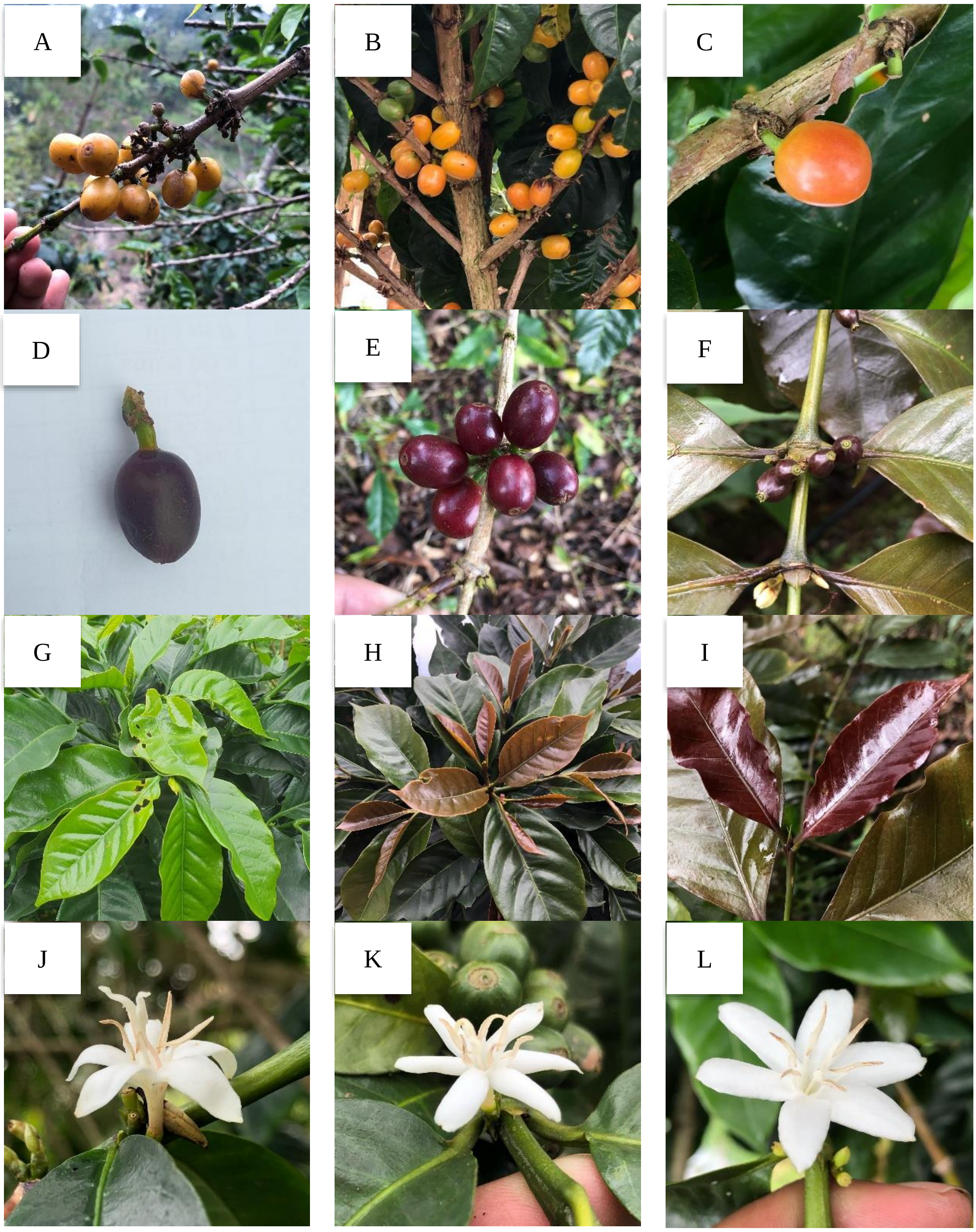

Figure 2. Variations in morphological characteristics: fruit color A: yellow, B: semi-orange yellow, C: orange, D: purple, E: purple violet, and F: violet. Young leaf color G: greenish, H: brownish, and I: purple. Stigma position toward anther J: excluded, K: parallel, and L: included

CONCLUSION

1. Fifteen *Coffea arabica* L. accessions with distinct fruit color from Temanggung exhibited average moderate (H'=0.721) qualitative morphological diversity. Fruit color, the primary distinguishing trait, showed high diversity (H' = 1.552), comprising six ripe fruit color categories, with orange being the dominant phenotype.

2. Cluster analysis grouped the 15 accessions into two major clusters with similarity coefficients ranging from 0.27 to 0.75, while accession 12 (12-P.Violet-BNS) formed a distinct branch, indicating its unique qualitative morphological characteristics.
3. The observed morphological diversity represents a valuable resource for accession identification, germplasm conservation, and the selection of promising breeding materials, which is important for breeding programs aimed at developing superior and environmentally adaptive Arabica coffee cultivar. Accessions with ripe fruit colors other than red also provide promising material for future research, particularly in molecular characterization, environmental adaptation, and sensory quality evaluation.

ACKNOWLEDGEMENT

The researchers would like to thank various parties who have helped and supported this research, especially coffee farmers in Temanggung Regency who have been willing to provide information and permission.

REFERENCES

Abdelwahab, S. I., Elhassan Taha, M. M., Jerah, A. A., Aljahdali, I. A., Oraibi, B., Alfaifi, H. A., Abdullah, S. M., Alzahrani, A. H., Oraibi, O., Babiker, Y., & Farasani, A. (2024). Coffee arabica research (1932–2023): Performance, thematic evolution and mapping, global landscape, and emerging trends. *Heliyon*, *10*(16), 1-15. https://doi.org/10.1016/j.heliyon.2024.e36137.

Andini, R., Zaelani, A., Sulaiman, M. I., Sembiring, E. R., Jaya, R., Gusain, M., Bhanot, D., Morghade, R. S., Gaafar, A.-R. Z., Azis, A., & Widayat, H. P. (2025). Genetic diversity of cultivated Gayo Arabica Coffee (*Coffea arabica* L.) based on morphological and microsatellite markers. *BMC Plant Biology*, 25, 990. https://doi.org/10.1186/s12870-025-06768-4

Ashardiono, F., & Trihartono, A. (2024). Optimizing the potential of Indonesian coffee: A dual market approach. *Cogent Social Sciences*, *10*(1), 1-17. https://doi.org/10.1080/23311886.2024.2340206

Atmoko, A. H., Aradea, B., Ramadhani, B. A. F., Oktavia, A. N., & Indrawati, E. (2026). Morphological Variation Among Robusta Coffee (*Coffea canephora*) Accesions in Temanggung as a Basis for Selection. *Berita Biologi*, 25(1), 281–300. https://doi.org/10.55981/berita_biologi.2026.11412

Azam, M. G., Hossain, M. A., Sarker, U., Alam, A. K. M. M., Nair, R. M., Roychowdhury, R., Ercisli, S., & Golokhvast, K. S. (2023). Genetic Analyses of Mungbean [*Vigna radiata* (L.) Wilczek] Breeding Traits for Selecting Superior Genotype(s) Using Multivariate and Multi-Traits Indexing Approaches. *Plants*, *12*(10), 1-28. https://doi.org/10.3390/plants12101984

Badan Pusat Statistik Kabupaten Temanggung. (2025). Produksi

Perkebunan. Accessed April 2nd, 2025, from https://temanggungkab.bps.go.id/id/statistics-table/2/MjI1IzI=/produksi-perkebunan.html

Baptistella, J. L. C., Assoni, G., da Silva, M. S., & Mazzafera, P. (2024). Variation in Soluble Sugars in Arabica Coffee Cherry Fruits. *Plants*, *13*(13), 1-11. https://doi.org/10.3390/plants13131853

Busch, J. W., Bodbyl-Roels, S., Tusuubira, S., & Kelly, J. K. (2022). Pollinator loss causes rapid adaptive evolution of selfing and dramatically reduces genome-wide genetic variability. *Evolution; International Journal of Organic Evolution*, *76*(9), 2130–2144. https://doi.org/10.1111/evo.14572

Campuzano-Duque, L. F., & Blair, M. W. (2022). Strategies for Robusta Coffee (*Coffea canephora*) Improvement as a New Crop in Colombia. *Agriculture*, 12(10), 1-14. https://doi.org/10.3390/agriculture12101576

Geleta, M., Herrera, I., Monzón, A., & Bryngelsson, T. (2012). Genetic diversity of arabica coffee (*Coffea arabica* L.) in Nicaragua as estimated by simple sequence repeat markers. *The Scientific World Journal*, *2012*, 1-11. https://doi.org/10.1100/2012/939820

Gonzali, S., & Perata, P. (2021). Fruit Colour and Novel Mechanisms of Genetic Regulation of Pigment Production in Tomato Fruits. *Horticulturae*, *7*(8), 1-18. https://doi.org/10.3390/horticulturae7080259

Govindaraj, M., Vetriventhan, M., & Srinivasan, M. (2015). Importance of Genetic Diversity Assessment in Crop Plants and Its Recent Advances: An Overview of Its Analytical Perspectives. *Genetics Research International*, *2015*, 1-14. https://doi.org/10.1155/2015/431487

Hernández-Alcántara, G., Alarcón-Gutiérrez, E., Ronzón-Soto, S., & García-Pérez, J. A. (2023). Physical and sensorial quality of yellow caturra coffee after a carbonic maceration process. *Coffee Science*, *18*(2023), 1-9. https://doi.org/10.25186/.v18i.2134

Hopkins, M. J., & Gerber, S. (2017). Morphological Disparity. In *Evolutionary Developmental Biology* (pp. 1–12). Springer, Cham. https://doi.org/10.1007/978-3-319-33038-9_132-1

Hu, F., Bi, X., Liu, H., Fu, X., Li, Y., Yang, Y., Zhang, X., Wu, R., Li, G., Lv, Y., Huang, J., Luo, X., & Shi, R. (2022). Transcriptome and carotenoid profiling of different varieties of Coffea arabica provides insights into fruit color formation. *Plant Diversity*, 44(3), 322–334. https://doi.org/10.1016/j.pld.2021.11.005

Huang, H.-Y., & Hsieh, C.-H. (2017). Genetic Research on Fruit Color Traits of the Bitter Gourd (*Momordica charantia* L.). *The Horticulture Journal*, *86*(2), 1-6. https://doi.org/10.2503/hortj.MI-159

Institute, I. P. G. R. (1996). *Descriptors for coffee (Coffea spp. And Psilanthus spp.)*. International Plant Genetic Resources Institute.

https://hdl.handle.net/10568/72788

International union for The Protection of New Varieties of Plants (Ed.). (2008). *Coffee: Guidelines for the Conduct of Tests for Distinctness, Uniformity and Stability*. International Union for the Protection of New Varieties of Plants. https://doi.org/10.34667/tind.58017

Jing, K., Chen, H., Kanika, N. H., Zhang, P., Mandal, R. N., Zeng, C., Zhang, Z., Wang, J., & Wang, C. (2025). Qualitative and quantitative characteristics of black patch trait in Oujiang color common carp. *Aquaculture Reports*, *40*(2025), 1-8. https://doi.org/10.1016/j.aqrep.2025.102619

Jm, G., Co, O., & Cw, K. (2015). Coffee improvement by interspecific hybridization: A review. *Journal of Agricultural and Crop Research*, 3(3), 41-46.

Kobylińska, Z., Biesiadecki, M., Kuna, E., Galiniak, S., & Mołoń, M. (2025). Coffee as a Source of Antioxidants and an Elixir of Youth. *Antioxidants*, *14*(3), 1-24. https://doi.org/10.3390/antiox14030285

Li, F., Song, X., Wu, L., Chen, H., Liang, Y., & Zhang, Y. (2018). Heredities on fruit color and pigment content between green and purple fruits in tomato. *Scientia Horticulturae*, *235*(2018), 391–396. https://doi.org/10.1016/j.scienta.2018.03.030

Malek, M. A., Rafii, M. Y., Shahida Sharmin Afroz, Most., Nath, U. K., & Mondal, M. M. A. (2014). Morphological Characterization and Assessment of Genetic Variability, Character Association, and Divergence in Soybean Mutants. *The Scientific World Journal*, *2014*(1), 1-10. https://doi.org/10.1155/2014/968796

Maxiselly, Y., Atiningsih, F. G., Rasiska, S., Hutapea, D., Bakti, C., Wahyudin, A. A., & Maharani, Y. (2025). Morphological diversity of arabica coffee (*Coffea arabica*) by in-situ exploration in three agroecosystems West Java, Indonesia. *Coffee Science*, 20, e202345–e202345. https://doi.org/10.25186/.v20i.2345

Mendes, G. de A., Oliveira, M. A. L. de, Rodarte, M. P., Anjos, V. de C. dos, & Bell, M. J. V. (2024). Determination of Arabica and Robusta species in blends of roasted coffee by Mid Infrared spectroscopy in association with mixture design. *Food Chemistry Advances*, *4*(2024), 1-7. https://doi.org/10.1016/j.focha.2023.100592

Mohammadi, S. A., & Prasanna, B. M. (2003). Analysis of Genetic Diversity in Crop Plants—Salient Statistical Tools and Considerations. *Crop Science*, 43(4), 1235–1248. https://doi.org/10.2135/cropsci2003.1235

Osorio Pérez, V., Matallana Pérez, L. G., Fernandez-Alduenda, M. R., Alvarez Barreto, C. I., Gallego Agudelo, C. P., & Montoya Restrepo, E. C. (2023). Chemical Composition and Sensory Quality of Coffee Fruits at Different Stages of Maturity. *Agronomy*, *13*(2), 1-15. https://doi.org/10.3390/agronomy13020341

Rohlf, F. E. J. (1992). *NTSYS-pc Numerical Taxonomy and Multivariate Analysis System, version 2.1: Owner manual*. Setauket, New York.

Romano, L. S., Giomo, G. S., Coelho, A. P., Filla, V. A., & Lemos, L. B. (2022). Characterization of Yellow Bourbon coffee strains for the production of differentiated specialty coffees. *Bragantia*, *81*, 1-13. https://doi.org/10.1590/1678-4499.20210236

Salgotra, R. K., & Chauhan, B. S. (2023). Genetic Diversity, Conservation, and Utilization of Plant Genetic Resources. *Genes*, *14*(1), 1-20. https://doi.org/10.3390/genes14010174

Salojärvi, J., Rambani, A., Yu, Z., Guyot, R., Strickler, S., Lepelley, M., Wang, C., et al. (2024). The genome and population genomics of allopolyploid Coffea arabica reveal the diversification history of modern coffee cultivars. *Nature Genetics*, *56*(4), 721–731. https://doi.org/10.1038/s41588-024-01695-w

Shu, H., He, C., Mumtaz, M. A., Hao, Y., Zhou, Y., Jin, W., Zhu, J., Bao, W., Cheng, S., Zhu, G., & Wang, Z. (2023). Fine mapping and identification of candidate genes for fruit color in pepper (*Capsicum chinense*). *Scientia Horticulturae*, *310*(2023), 1-9. https://doi.org/10.1016/j.scienta.2022.111724

Tounekti, T., Mahdhi, M., Al-Turki, T. A., & Khemira, H. (2017). Genetic Diversity Analysis of Coffee (*Coffee arabica* L.) Germplasm Accessions Growing in the Southwestern Saudi Arabia Using Quantitative Traits. *Natural Resources*, 8(5), 321–336. https://doi.org/10.4236/nr.2017.85020

Unigarro, C. A., Cayón Salinas, D. G., León-Burgos, A. F., & Flórez-Ramos, C. P. (2025). Flowering and Fruiting of Coffea arabica L.: A Comprehensive Perspective from Phenology. *Plants*, *14*(21), 1-25. https://doi.org/10.3390/plants14213396

Yeshitila, M., Gedebo, A., Tesfaye, B., & Degu, H. D. (2024). Agro-morphological genetic diversity assessment of Amaranthus genotypes from Ethiopia based on qualitative traits. *CABI Agriculture and Bioscience*, *5*(1), 1-23. https://doi.org/10.1186/s43170-024-00288-1

Yirgu, M., Kebede, M., Feyissa, T., Lakew, B., & Woldeyohannes, A. B. (2022). Morphological variations of qualitative traits of barley (*Hordeum vulgare* L.) accessions in Ethiopia. *Heliyon*, *8*(10), 1-12. https://doi.org/10.1016/j.heliyon.2022.e10949

Zhang, Q., Ma, D., Yang, Y., Hu, F., Fu, X., Li, G., Zhang, X., Wang, N., Liu, D., Wu, R., Bi, X., Lou, Y., Li, Y., Yu, H., Yan, W., & Li, Y. (2024). Population Genetic Characteristics of the Cultivated Coffea arabica with Whole-Genome Resequencing. *Horticulturae*, 10(11), 1153. https://doi.org/10.3390/horticulturae10111153