Genotyping and Morphological Characterization of Arabica Coffee (*Coffea arabica*): A Review

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Abstract- Arabica coffee (*Coffea arabica* L.) is a globally important crop valued for its superior beverage quality and economic significance to smallholder farmers in tropical regions, including the Philippines. However, the true identity and genetic diversity of locally cultivated Arabica varieties remain poorly documented due to widespread informal seed exchange and limited characterization efforts. This short review synthesizes current knowledge on morphological characterization and molecular genotyping approaches used in the assessment of Arabica coffee diversity. Morphological descriptors remain useful for field-level varietal identification and agronomic evaluation, although phenotypic traits are strongly influenced by environmental conditions. Molecular markers such as simple sequence repeats (SSR) and inter-simple sequence repeats (ISSR) provide more reliable insights into genetic relationships, varietal identity, and germplasm conservation. Studies conducted in the Philippines and other coffee-producing countries demonstrate that integrating morphological and molecular approaches improves accuracy in classification and supports breeding programs. Despite growing interest in coffee characterization, significant gaps remain in Philippine Arabica research, particularly in advanced genomic studies and genotype–environment interaction analysis. Strengthening integrated characterization efforts is essential for conservation, varietal improvement, and sustainable coffee production.

Index Terms- *Coffea arabica*, Morphological characterization, Molecular markers, Genetic diversity, Germplasm conservation

I. Introduction

Coffee (Coffea spp.) is among the world's most traded agricultural commodities (Belay et al., 2015; Shara et al., 2021) and is essentially the major source of income for millions of farmers living in the tropical regions (International Coffee Organization, 2023; Pancsira, 2022). Globally, Arabica coffee (*Coffea arabica* L.) is responsible for about 60–70% of total coffee production mainly due to its better flavor, aroma, and overall cup quality as compared to other species like *Coffea canephora* (Robusta) and *Coffea liberica* (Excelsa) (Davis et al., 2012; DaMatta et al., 2019). The Arabica plant grows well in areas at high elevations with cool temperatures, rich soils, and sufficient rainfall – such as those found in the upland regions of the Philippines including Benguet, Sagada, Davao del Sur, and Bukidnon (Philippine Statistics Authority, 2023).

Coffee is a culturally and economically significant crop in the Philippines, with around 110,000 hectares of land being used for its cultivation (Department of Agriculture – Bureau of Plant Industry, 2022; Luat et al., 2022). Arabica is mostly grown in the upper areas of the provinces of Luzon and Mindanao, where agroclimatic conditions are favorable for cultivation and cup quality (Tad-Awan et al., 2013). Arabica production in Bukidnon, is expanding as a result of the increasing demand for good quality specialty coffee and the support of the government for the coffee revitalization programs (Department of Trade and Industry Bukidnon, 2021). However, the diversity and true identity of the Arabica varietals grown by local farmers are generally unknown. Many farmers rely on seedlings of unknown genetic origin, which are frequently propagated from neighbor farms or unconfirmed sources, resulting in varietal mixing, loss of genetic purity, and uneven yield and quality (Baltazar & Fabella, 2020).

It is essential to understand the genetic and morphological diversity of Arabica coffee populations for the purposes of varietal identification, conservation, and crop improvement (Andini et al., 2025). Morphological characterization is an approach that relies on the examination of the outward features of the plant such as height of the plant, shape of the leaf, color of the fruit, and length of the internode and can still be considered a fundamental method in discovering the differences between varieties and serving as a guide for staff working the selection in the farm plot (Santos et al., 2011). Studies in Benguet and other Philippine regions have demonstrated that morphological features can differ greatly between accessions, reflecting both genetic differences and environmental impacts (Tad-awan et al., 2018). However, the morphological traits of a specimen are highly unlikely to be a perfect representation of the genetic variation that lies under the surface because it could be changed significantly by the environment and the care given to the plant (Shara et al., 2021).

Besides morphology, molecular instruments like genotyping with DNA-based markers (for instance, Simple Sequence Repeats [SSR] and Inter-Simple Sequence Repeats [ISSR]) can give a much clearer view of genetic diversity and the relationships of the coffee samples (Andini et al., 2025; Baltazar & Fabella, 2020). Molecular marker research has played a key role in confirming varietal identity, uncovering genetic contamination, and recognizing the best genotypes for the breeding of new varieties. A case in point is the work of Baltazar and Fabella (2020) who, employing SSR markers, examined the genetic diversity of Philippine Arabica accessions and found a moderate level of genetic polymorphism which pointed at the presence of a significant amount of genetic variation for selection and conservation. Similarly, Panaligan et al. (2020) presented evidence that ISSR markers can be used for the identification of coffee species and varieties that are standard practice in the Philippines.

The combination of morphological characterization and genotyping provides a powerful tool for the study of coffee diversity as it allows the integration of both phenotypic and genotypic data. Research conducted in Indonesia and Ethiopia has shown that such integrative methods improve the accuracy of varietal identification and make it easier to implement conservation measures for genetically diverse and locally adapted coffee genotypes (Andini et al., 2025; DaMatta et al., 2019). Besides, relationships between morphological characters and genetic information may indicate to what extent the visible differences reflect the genetic differentiation (Hu et al., 2019).

Characterization of coffee germplasm is vital to examining genetic variability. Traditional morphological characterization of breeding materials is commonly used for the differentiation of coffee varieties, including the assessment of agronomic performance. Advances in molecular biology have led to the development of genotyping techniques that deliver precise genetic information. Integration of morphological and molecular approaches can provide a comprehensive understanding of Arabica coffee diversity. Despite increasing global research on coffee genetics, integrated reviews focusing on morphological and molecular characterization relevant to Philippine Arabica coffee remain limited. This review critically evaluates current characterization approaches and synthesizes major findings to support future breeding and conservation strategies.

II. LITERATURE SEARCH STRATEGY

This review synthesized peer-reviewed literature related to morphological characterization and molecular genotyping of Arabica coffee. Scientific articles were collected from databases including Scopus, Google Scholar, and Web of Science using keywords such as "*Coffea arabica*," "morphological characterization," "genetic diversity," "SSR markers," "ISSR markers," and "coffee germplasm." Recent studies published were prioritized, although key foundational references were also included. Articles were selected based on relevance to coffee diversity assessment, varietal identification, and integration of morphological and molecular methods.

A. Origin and Botanical Description Of Coffee

Coffee (*Coffea spp.)* is believed to have originated in the southwestern highlands of Ethiopia, where *Coffea arabica* was first identified (Chauhan & Tanga, 2015). Today, it is widely cultivated in tropical and subtropical regions worldwide, with major producers including Brazil, Vietnam, Colombia, Indonesia, and Ethiopia (USDA, 2025). Coffee belongs to the family Rubiaceae, subfamily Ixoroideae, which comprises over 500 genera and more than 6,000 species (Harnelly et al., 2024; Razafimandimbison & Rydin, 2024). The genus Coffea includes multiple species, with *C. arabica* and *C. canephora* (robusta) being the most commercially significant. Recent taxonomic revisions have consolidated several subgenera and related genera under the current Coffea classification (Ferreira et al., 2019).

The coffee plant is an evergreen perennial, naturally living 10–15 years in wild conditions, though commercial plantations require regular regeneration due to declining fruit production over time (Farah & Ferreira dos Santos, 2015). Morphologically, coffee exhibits an upright main shoot (trunk) with lateral branches categorized as primary, secondary, and tertiary. Young lateral shoots, known as suckers, bear decussate, opposite leaves; these develop into mature stems over time. Flowers are borne in axillary clusters, with seeds (coffee beans) developing in the ovary, characteristic of angiosperms (Ferreira et al., 2019). Botanical characterization of coffee includes traits such as leaf size and shape, branching pattern, internode length, flower morphology, fruit size and color, and seed characteristics. These traits are essential for genotypic and phenotypic differentiation among Coffea species and varieties, providing critical information for breeding, cultivation, and genetic improvement programs (Farah & Ferreira dos Santos, 2015).

B. Arabica Coffee

Coffea arabica, an evergreen shrub or small tree, can reach heights of up to 5 meters when left unpruned. It has small, straightforward, glossy, dark green leaves (Orwa et al., 2009). Arabica is an allotetraploid ($2n = 4x = 44$), descended from two distinct diploid ($2n = 2x = 22$) wild ancestors, C. canephora and S. eugenioides S. (Jurghen Pohlan & Janssens, 2010). Recent whole-genome sequencing confirms that this was likely a single polyploidization event occurring between 10,000 to 50,000 years ago; this "genomic bottleneck" is the primary reason for the species' extremely low genetic variation globally (Scalabrin et al., 2020). The plant arabica self-pollinates and reproduces, it also has lower caffeine content compared to Robusta (Poltronieri & Rossi, 2016).

Coffea Arabica is very valuable due to its exceptional quality and flavor profile. High-quality Arabica beans are frequently connected with regions known for its coffee production (Khemira et al., 2023). Growing factors like as altitude, climate, soil composition, and cultivation practices have a significant impact on coffee flavor and aroma. Arabica cultivation requires certain conditions to grow. It is often grown at higher altitudes of 600 to 2000 meters (2000 to 6500 feet) above sea level (Sayed et al., 2019). Arabica is considered a significant economic commodity worldwide due to its popularity and demand (Vaast et al., 2005). The growing global demand for high-quality Arabica coffee has led to the need for improved coffee types with high yield, resistance to environmental stress, and good cup quality. To identify and develop local coffee germplasm, cutting-edge scientific tools are urgently needed (Bramel et al., 2017).

C. Morphological Characterization of Coffee Plants

Morphological characterization is a classical method but still a very important approach used in the identification of coffee varieties. It means looking at the different characters like the height of the plant, the color of the leaf, the structure of the branch, and the morphology of the fruit to explain the intraspecific diversity as stated in the book of Bioversity International (1996). According to Shara et al. (2021), the authors claim that differences in the vegetative traits especially leaf shape and size, internode length, and stem thickness can be used to differentiate coffee accessions. Tad-awan et al. (2018) observed considerable phenotypic differences among the Arabica accessions in Benguet and thus, explained this by both genetic and environmental factors. These descriptors are set by Bioversity International to allow the same evaluation in different places.

Nevertheless, the differences in morphology might not always reflect the genetic diversity because the environment and the way the plants are grown may affect them (Santos et al., 2011). For instance, the influence of shading, soil fertility, and altitude on the phenotypic expression of the Arabica plants (DaMatta et al., 2019). Consequently, morphological data are most effective if they are accompanied by molecular analyses. The latest studies on characterization in Indonesia and Vietnam have supported this view that although phenotypic clustering can be done, the accuracy in varietal classification is much higher when genotypic data are integrated (Hu et al., 2019). Across reviewed studies, morphological characterization consistently revealed high phenotypic variability among Arabica accessions. However, environmental effects such as altitude, shading, and soil fertility strongly influence phenotypic expression, limiting the reliability of morphology as a standalone tool for genetic classification. Because manual descriptors are labor-intensive and prone to human error, the field is transitioning toward digital plant phenotyping (Yang et al., 2020). High-throughput phenotyping (HTP) uses image-based sensors and AI to objectively measure traits like canopy architecture and drought response, which are critical for identifying climate-resilient genotypes in the field (Li et al., 2023).

Table 1: Morphological Characterization Studies in Arabica Coffee

Author	Country	Traits Evaluated	Major Findings	Limitations
Tad-awan et al. (2018)	Philippines	Leaf, plant height, growth habit	High phenotypic variability among accessions	Environmental influence
Shara et al. (2021)	Indonesia	Vegetative traits	Useful for field identification	Low genetic resolution
Bioversity International (1996)	Global	Standard descriptors	Standardized evaluation methods	Requires molecular support
Teshome et al. (2023)	Ethiopia	Leaf size, berry morphology	Phenotypic variation linked to local adaptation	Environment-dependent traits
Harnelly et al. (2024)	Indonesia	Leaf morphology, plant structure	Effective preliminary classification	Limited genetic accuracy
Andini et al. (2025)	Indonesia	Growth and morphological descriptors	Significant phenotypic diversity	Needs molecular confirmation
Orwa et al. (2009)	Global	Plant morphology	Useful botanical reference for Arabica description	Not population-level diversity
DaMatta et al. (2019)	Global	Physiological and morphological responses	Morphology influenced by environmental stress	Not suitable for genetic inference alone

Morphological characterization studies conducted across multiple coffee-producing regions consistently report high phenotypic variability among Arabica accessions, although environmental influence limits their use as standalone indicators of genetic diversity (Table 1).

D. Genotyping and Molecular Marker Studies in Coffee

The introduction of molecular markers has revolutionized plant genetic analysis and has become a cornerstone of coffee breeding. Among the markers, SSR (Simple Sequence Repeats) and ISSR (Inter-Simple Sequence Repeats) are now widely preferred due to their reliability in detecting genetic polymorphisms, which reveal the genetic structure and degree of relatedness among coffee accessions (Baltazar & Fabella, 2020). In the Philippines, SSR analyses of local Arabica accessions indicate moderate genetic variation, reflecting both a narrow genetic base and occasional gene flow from other species (Panaligan et al., 2020). On a global scale, SSR markers have been successfully used to distinguish Gayo Arabica varieties, highlighting their importance for germplasm conservation (Andini et al., 2025).

Genotyping with DNA markers enables the construction of dendrograms to visualize genetic relationships and cluster different varieties. It is also applied in parentage verification and identification of true-to-type seedlings (Tad-awan et al., 2018). The combined use of SSR and ISSR markers is particularly advantageous for detecting intra-varietal variability and hybridization events. Recent molecular coffee programs demonstrate that genotyping not only supports varietal authentication but also guides the selection of parents for hybrid development with improved resistance and quality traits (Pereira et al., 2020).

While SSRs and ISSRs provide a moderate level of polymorphism, they often lack the resolution needed to distinguish closely related Arabica varieties. Modern coffee genomics is shifting toward Single Nucleotide Polymorphism (SNP) markers, such as the 8.5K SNP

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array developed by Merot-L'anthoene et al. (2019), which allows for precise varietal authentication and identification of genetic contamination.

Compared with morphological approaches, molecular markers provide higher resolution in detecting genetic variation and confirming varietal identity. SSR markers, in particular, are the most frequently applied tool in Arabica diversity studies due to their reproducibility, co-dominant inheritance, and high polymorphism. This molecular approach complements traditional phenotypic characterization, enabling more precise and efficient breeding and conservation strategies.

Table 2: Molecular Marker Studies in Arabica Coffee

Author	Marker Type	Country	Purpose	Key Findings	Application
Baltazar & Fabella (2020)	SSR	Philippines	Genetic diversity	Moderate polymorphism detected	Breeding & conservation
Panaligan et al. (2020)	ISSR	Philippines	Variety identification	Species discrimination effective	Germplasm management
Andini et al. (2025)	SSR	Indonesia	Genetic clustering	Differentiated Arabica varieties	Conservation planning
Tad-awan et al. (2018)	SSR	Philippines	Diversity analysis	Genetic grouping of accessions	Varietal verification
Pereira et al. (2020)	DNA markers	Brazil	Breeding applications	Parent selection improved	Hybrid development
Teshome et al. (2023)	SSR	Ethiopia	Diversity analysis	Genetic differentiation detected	Breeding resource
Hu et al. (2019)	Molecular markers	China	Genetic divergence	Moderate correlation with morphology	Evolutionary studies
Davis et al. (2012)	Genetic analysis	Global	Species diversity	Genetic vulnerability of Arabica	Conservation
Poltronieri & Rossi (2016)	DNA tools	Global	Genetic characterization	Improved varietal authentication	Quality control
Bramel et al. (2017)	Genetic resources	Global	Germplasm conservation	Importance of genetic diversity	Global breeding strategy

Molecular marker studies demonstrate the effectiveness of SSR and ISSR markers in revealing genetic relationships, confirming varietal identity, and supporting breeding programs (Table 2).

E. *Correlation Between Morphological and Genetic Diversity*

One of the key aspects to locating mutations and figuring out how they pass from one generation to another in the most efficient way is the correlation between morphological and genetic diversity (Malek et al., 2014). Various studies have revealed that both methods show the differences; however; the correspondence between them is weak to moderate depending on the environmental factors when morphological descriptors are combined with genotyping (Andini et al., 2025; Hu et al., 2019). Since morphological similarity may not necessarily indicate genetic closeness, it is advisable to use integrated approaches for proper classification.

In Arabica coffee, relationships between morphological clustering and molecular phylogenetic groupings are frequently partial but significant enough to support phenotypic selection (Shara et al., 2021). DaMatta et al. (2019) pointed out that genetic expression could be completely hidden by the environment, and hence the need for molecular instruments for accurate identification. The Mantel test is commonly used to find the degree of correlation between morphological and molecular data matrices that helps in evaluating the trustworthiness of field-based varietal identification (Baltazar & Fabella, 2020). The use of both morphological and genotypic data is one of the necessary steps to understand diversity fully, which is essential for the conservation and breeding programs.

Recent research highlights the necessity of combining both the morphological and molecular examinations to obtain a broader understanding of plant diversity and varietal identity. In such study on *Coffea arabica*, Teshome et al. (2023) found that phenotypic traits such as leaf size, berry shape, and branching habit were only partially in line with genetic grouping based on SSR markers, thus indicating the influence of both heredity and local adaptation. Additionally, Fernandez et al. (2022) proved that the simultaneous use of morphological and molecular data leads to a higher correct rate of genotype identification and better prediction of the agronomic performance. Consequently, linking morphological and molecular variation serves not only as a tool for verification of classification conducted in the field but also as a scientific ground for the selection and conservation of elite genotypes in coffee breeding programs. Studies consistently report weak to moderate correlations between phenotypic and genotypic data, highlighting the importance of integrated approaches for accurate varietal classification.

While studies in the Gayo highlands of Indonesia show significant phenotypic diversity linked to local adaptation (Andini et al., 2025), Philippine Arabica populations in Benguet and Bukidnon face similar challenges of varietal mixing. Comparing these regions reveals that while Gayo varieties have been mapped for specific cup profiles, Philippine landraces require urgent high-resolution genotyping to establish a similar "regional brand" based on genetic purity (Mishra & Slater, 2022).

F. Comparative Synthesis of Morphological and Molecular Approaches

Across reviewed studies, morphological characterization remains valuable for rapid field-level evaluation and preliminary classification of Arabica coffee accessions. However, variability in phenotypic expression caused by environmental conditions often limits its effectiveness as a standalone method. Molecular markers provide more stable indicators of genetic relationships and are widely used to confirm varietal identity and detect hybridization events. Most studies recommend integrating morphological descriptors with molecular genotyping to achieve accurate classification and support breeding programs. This combined approach allows researchers to correlate visible agronomic traits with underlying genetic diversity.

Table 3: Comparative Analysis of Morphological vs Molecular Approaches

Criteria	**Morphological Characterization**	**Molecular Genotyping**
Data Type	Phenotypic traits	DNA-level variation
Reliability	Moderate	High
Environmental Influence	High	Very low
Field Application	Easy and inexpensive	Requires laboratory facilities
Genetic Resolution	Limited	Precise
Cost	Low	Moderate to high
Use in Breeding	Preliminary selection	Parent verification
Use in Conservation	Initial diversity assessment	Accurate germplasm identification
Major Limitation	Phenotypic plasticity	Technical expertise required
Best Approach	Combined with molecular tools	Combined with morphology

A comparative analysis of morphological and molecular approaches highlights the complementary strengths of both methods and supports the use of integrated characterization strategies (Table 3).

III. PRACTICAL IMPLICATIONS FOR COFFEE BREEDING AND CONSERVATION

The use of molecular markers in coffee has direct practical applications. They facilitate the selection of superior parents for hybridization, enabling the development of varieties with enhanced resistance and quality traits. Molecular tools also support germplasm conservation by accurately identifying and cataloging genetic resources (Huded et al., 2026). Furthermore, varietal authentication ensures the true-to-type identity of planting materials, which strengthens seed systems and improves the reliability of distribution to farmers, ultimately enhancing productivity and sustainability.

Beyond breeding, accurate genotyping has a direct economic impact on smallholder farmers. In the Philippines, where informal seed exchange is common, molecular verification prevents the accidental cultivation of mislabeled or inferior "fake" varieties, ensuring that the farmer's long-term investment in a five-year growth cycle is protected by guaranteed genetic quality (Sousa et al., 2023). Furthermore, this supports Genomic Selection (GS), which can predict yield and quality traits years before the tree reaches maturity (Sant'Ana et al., 2018).

High-resolution genotyping supports Genomic Selection (GS), which uses DNA markers to predict complex traits such as yield and cup quality. By implementing GS, breeders can evaluate the potential of a coffee tree years before it reaches maturity, drastically shortening the breeding cycle. This is particularly vital for the Philippines, as it ensures that the long-term investment made by smallholder farmers is protected by planting materials with guaranteed genetic quality.

Research Gaps

Despite the progress in morphological and molecular characterization, several critical gaps remain, particularly within the context of the Philippine coffee industry:

• Climate-Resilient Genotyping: While global research has begun identifying genotypes with higher resilience to thermal and moisture stress, there is a significant lack of data on how Philippine Arabica accessions respond to climate change-driven abiotic stressors. Recent studies underscore that Arabica's narrow genetic base makes it exceptionally vulnerable to rising temperatures and erratic rainfall (Bilen et al., 2022; Ahmed et al., 2021). There is an urgent need to use molecular markers to identify local "climate-smart" landraces that exhibit natural tolerance to heat and drought—traits that are increasingly vital as traditional coffee-growing regions shift to higher altitudes (Bosly et al., 2025). National strategies must align with the Global Coffee Varieties Catalogue to ensure that local "climate-smart" landraces are not only identified but also globally recognized for their unique traits (World Coffee Research, 2019; Carvalho et al., 2022).

• Genotype–Environment (G×E) Interaction Analysis: Most local studies remain focused on static morphological descriptions. There is a need for multi-location trials to understand how specific genotypes perform under varying microclimates, especially concerning cup quality and pest resistance under projected El Niño scenarios (Rodriguez-Camayo et al., 2024).

• Transition to High-Throughput Genomics: Philippine research still relies heavily on low-resolution markers like SSR and ISSR. Transitioning to Single Nucleotide Polymorphism (SNP) markers and high-throughput sequencing is necessary to achieve the "genetic resolution" required for modern breeding programs and to ensure the climate-proofing of the industry (Abdelwahab et al., 2024).

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VI. CONCLUSION

Morphological and molecular characterization approaches play complementary roles in understanding the diversity of Arabica coffee. While morphological traits remain useful for field-level identification and agronomic assessment, molecular markers provide more reliable insights into genetic relationships and varietal identity. Studies reviewed demonstrate that integrating phenotypic and genotypic data improves classification accuracy and supports breeding and conservation programs. However, research on Philippine Arabica coffee remains limited, particularly in advanced genomic analysis and climate-adaptive trait evaluation. Strengthening integrated characterization efforts will be crucial for preserving genetic resources, improving varietal performance, and ensuring the long-term sustainability of Arabica coffee production.

APPENDIX

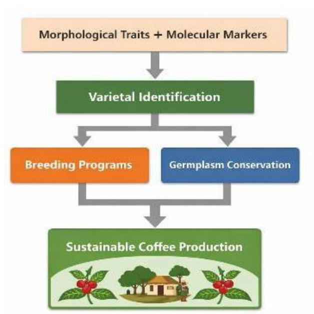

Figure 1: Conceptual Framework for Integrated Characterization.

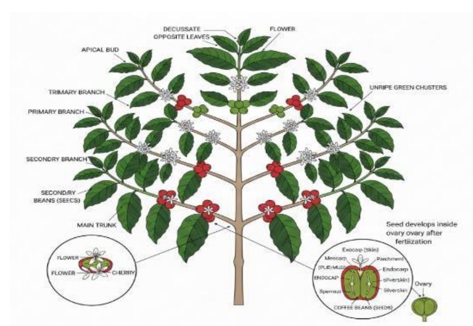

Figure 2. The Botanical Structure/Morphology of Coffee.

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