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Short Communication: Morphological variation of *Coffea liberica* from Batangas, Philippines with implications for sustainable coffee production and breeding programs

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Abstract. *Balan AM, Mendoza PP, Salcedo ARM, Alejandro GJD. 2026. Short Communication: Morphological variation of* Coffea liberica *from Batangas, Philippines with implications for sustainable coffee production and breeding programs. Biodiversitas 26 (1): d270149. https://doi.org/10.13057/biodiv/d270149.* *Coffea liberica*, locally known as "*kapeng barako*" in the Philippines, represents an understudied yet economically significant coffee species with unique morphological characteristics and climate resilience. Despite its commercial presence across Southeast Asia and potential for specialty markets, comprehensive morphological assessments of Philippine C. *liberica* population remain limited. This single-site baseline study provides morphometric analysis of plants grown in Batangas, Philippines, investigating correlations between leaf architecture, fruit morphology, and bean characteristics to inform breeding and sustainable cultivation. Twelve coffee plants from a farm in Barangay Ludlod, Lipa, Batangas, were analyzed using standardized morphometric protocols. Statistical analyses included correlation analysis and ANOVA to examine relationships among leaf area, cherry volume, bean dimensions, and pulp thickness. Strong positive correlations were observed between leaf area and both cherry volume ($r = 0.84$, $p<0.05$) and bean volume ($r = 0.92$, $p<0.05$), indicating coordinated morphological development. Cherry and bean volumes showed moderate correlation, while pulp thickness correlated positively with both cherry and bean volumes and accounted for over half of variation in both traits. ANOVA revealed statistically significant differences in cherry size among individual plants, though the overall range of variation was relatively narrow compared to reported diversity in other coffee species. These findings establish baseline morphometric data for C. *liberica* from this site, demonstrating coordinated leaf-fruit development that may guide selection criteria for breeding. Results highlight the need for expanded multi-site studies to validate these relationships for improved productivity and climate adaptation strategies.

Keywords: *Coffea liberica*, correlation method, kapeng barako, morphological variation, sustainable agriculture

INTRODUCTION

The global coffee industry faces unprecedented challenges from climate change, with increasing heat, variable rainfall patterns, and severe pest infestations and plant diseases necessitating diversification beyond the dominant *Coffea arabica* L. and *Coffea canephora* Pierre ex A.Froehner species (Haile and Kang 2019). These stressors are destructive to both species, which together make up 98% of the global coffee supply (Cascos et al. 2023). *Coffea liberica* W.Bull presents unique opportunities for sustainable coffee production due to its exceptional environmental tolerance and distinctive sensory profile (Davis et al. 2022).

Three main coffee species are commercially cultivated: *C. arabica*, *C. canephora* (Robusta), and *C. liberica*. In the Philippines, *C. liberica* is locally known as "kapeng barako," meaning strong coffee, and was historically the main variety grown in Batangas and Cavite provinces (Lagman 2023). However, *C. liberica* accounts for only 2% of global coffee production (Halim-Lim et al. 2022). This underutilized species has potential for sustainable coffee breeding under adverse environmental conditions. *C. liberica* is known for its resilience to heat, drought, and varying climates, which makes it a viable candidate for cultivation in tropical regions that are highly affected by climate change (Wafaretta et al. 2023; Hafif et al. 2024). Numerous studies have been conducted on *C. arabica* and *C. canephora* that have served as a strong baseline in understanding the fundamental morphological, physiological, and agronomic characteristics (Panaligan et al. 2020; Davis et al. 2022; Alberto et al. 2024).

Morphological research on *C. liberica* remains severely limited, particularly in the Philippine context. While extensive morphometric studies exist for *C. arabica* and *C. canephora* (Bizimungu et al. 2022), systematic investigations of *C. liberica* morphological variation are virtually absent from Philippine scientific literature. Previous Philippine coffee genetics research has focused on *C. arabica* and *C. canephora* cultivars (Panaligan et al. 2020; Santos et al. 2023), leaving *C. liberica* understudied despite its economic and cultural importance. Studying the morphological variations in *C. liberica* plays an important role in understanding its adaptation, productivity, and breeding capability. In coffee, the leaf size can influence the photosynthetic capacity (Alberto et al. 2024; Silva et al. 2025), while the characteristics of the fruit and seed dictate the maximum possible yield and cup quality (Shara et al. 2021; Abubakar et al. 2024).

The maximum length of the leaves of *C. liberica* of variety liberica is 224±40 mm, while *C. canephora* is 208±24 mm, and *C. arabica* is 137±39 (Cao et al. 2014). While *C. arabica* fruit size (length x width) 1.68-1.88 cm x 1.30-1.42 cm, *C. canephora* average fruit size (length x width) is 1.28 cm x 1.16 cm, and *C. liberica* fruit size (length x width) is (1.5-)1.8-3.4 x 1.7-3.3 cm (Shara et al. 2021; Rahman et al. 2024; Davis et al. 2025).

C. liberica demonstrates adaptability to different growing conditions, high drought survival rates (Wafaretta et al. 2023), and optimal performance at altitudes of 600-1,000 m above sea level (Nurdin et al. 2022). The species is especially suited to sustainable agroforestry practices in tropical regions with high climate variability (Hafif et al. 2024). Its flavor profile, marked by light sweetness, chocolate notes, and tropical fruit hints, has attracted increasing interest in specialty coffee markets (Davis et al. 2022).

Understanding morphological relationships in *C. liberica* is essential for developing climate-resilient varieties and optimizing cultivation practices. Studies on other coffee species have demonstrated that leaf characteristics determine photosynthetic capacity and plant productivity (Alberto et al. 2024; Silva et al. 2025), while fruit and seed morphological traits significantly impact coffee quality (Shara et al. 2021; Abubakar et al. 2024). Similar comprehensive analyses for *C. liberica* in Southeast Asian contexts are needed.

Morphological data are very important in providing a baseline for phenotypic selection in breeding programs, particularly in the absence of molecular tools. Correlations between the vegetative traits and reproductive traits are very useful in the selection process for breeding especially if there are limited resources (Abubakar et al. 2024).

This study addresses this knowledge gap by establishing baseline morphometric parameters for Philippine *C. liberica* and analyzing correlations between vegetative and reproductive traits that may inform breeding programs and sustainable cultivation strategies. While limited to one site, the findings contribute to understanding morphological relationships requiring validation across multiple locations.

MATERIALS AND METHODS

Research location

The study was conducted on a farm in Barangay Ludlod, Lipa City, Batangas (13°55'52"N, 121°8'30"E, 328.2 m above sea level). The farm covers approximately 2 ha and cultivates *Coffea liberica* alongside other fruit-bearing trees. Permission to access the farm site and data collection was obtained from the owner.

Sampling, collection, and processing of specimens

A total of twelve coffee trees were selected using a systematic random sampling approach wherein the farm was divided into a grid and one tree was randomly selected from each grid section using a random number generator, ensuring spatial distribution across the cultivation area. This sample size is consistent with initial morphological characterization studies in perennial crops (Pompelli et al. 2012; Fernandez et al. 2022) and was deemed sufficient to capture the primary morphological variation within the farm for this baseline assessment. From each plant, ten fully matured leaves and ten fully matured cherries were collected during peak harvest season in February 2024 to ensure optimal fruit ripeness. Samples were placed in separate polyethylene bags and labeled according to standardized protocols. All measurements were conducted within 4 hours of collection to minimize post-harvest changes in morphological traits.

Morphological trait measurement

Twelve individual coffee plants served as biological replicates for this treatment. For each coffee plant, ten mature leaves and ten ripe cherries were measured to provide intra-plant replication. Replication across sites and environmental conditions was not conducted, which may have influenced heterogeneity in trait expression. These limitations recommend the importance of conducting multi-site studies with larger sample sizes to strengthen the generalizability of observed patterns.

Leaf morphometric measurements followed established protocols, employing a 30 cm plastic ruler with a precision of ±0.05 cm. Parameters measured included maximum length, blade length, maximum width, length above maximum width, length below maximum width, and petiole length, as shown in Figure 1.A Leaf area was estimated using the formula: Leaf Area = $(\pi \times \text{length} \times \text{width}) / 4$ (Pompelli et al. 2012), while aspect ratio was calculated as: Aspect ratio = width / length.

Cherry measurements were taken using a digital vernier caliper (±0.01 mm precision), recording diameter, length, and width as shown in Figure 1.B. Cherry area and volume were calculated using: Area = $(\pi \times \text{length} \times \text{width}) / 4$ and Volume = $\frac{2}{3}\pi \times \text{length} \times \text{width} \times \text{thickness}$ respectively (Bizimungu et al. 2022). These ellipsoid approximations provide accurate estimates for coffee cherry morphology.

Pulp thickness was measured with a digital vernier caliper after manual pulping. Bean measurements included length, diameter, and thickness. Bean aspect ratio and volume were determined using the same formulas applied to cherry measurements.

Statistical analysis

All statistical analyses were performed using IBM SPSS Statistics version 29.0. Descriptive statistics (means, standard deviations, minimum, maximum, and ranges) were calculated for each trait across the twelve sampled plants. Assumptions of normality and homogeneity of variances were tested using Shapiro-Wilk and Levene's tests, respectively.

Morphological relationships were examined through Pearson correlation coefficients, focusing on associations between leaf area, cherry volume, bean volume, and pulp thickness. Statistical significance was assessed at $\alpha = 0.05$, with corresponding p-values reported. Scatter plots with least-squares regression lines were generated to visualize correlations between leaf area and reproductive traits.

A one-way analysis of variance (ANOVA) was conducted to evaluate differences in cherry area among the twelve plants, with F-values and p-values used to determine significance.

RESULTS AND DISCUSSION

Leaf, cherry, and bean morphological characteristics

Morphological analysis revealed variation in key parameters across the twelve sampled plants (Table 1). Leaf area, a main factor of photosynthetic potential ranged from 191.12 to 460.64 cm² (mean: 308.74±75.18 cm²), representing a 2.4-fold difference. Cherry volume ranged from 4,405.3 to 11,438.0 mm³ (mean: 7,742.55±2,001.37 mm³), a 2.6-fold difference. Bean volume varied from 1,166.9 to 4,408.8 mm³ (mean: 2,832.91±866.00 mm³), nearly a four-fold difference.

Correlation between morphological traits

Correlation analysis revealed statistically significant relationships between key morphological traits (Table 2, Figure 2). All correlations were positive and significant at $\alpha = 0.05$ level.

Morphological variation analysis

One-way analysis of variance testing the effect of individual plant identity on cherry area revealed statistically significant differences among the twelve plants (Table 3), indicating genuine morphological variation within the sampled population.

Table 3. One-way ANOVA for the effect of individual plant identity on cherry morphological characteristics in *Coffea liberica* samples

Variable	F-value	p-value	Interpretation
Cherry area (mm²)	7.820	0.014*	Significant variation among plants

Note: *p<0.05; df = 11 (between plants), 120 (within plants)

Table 1. Summary statistics of morphological traits for *Coffea liberica* from Batangas, Philippines (n=12 plants)

Trait	Mean	SD	Min	Max	Range
Leaf characteristics					
Maximum length (cm)	30.18	3.19	25.70	36.00	10.30
Petiole length (cm)	2.23	0.28	1.90	2.70	0.80
Blade length (cm)	27.98	2.91	23.40	33.60	10.20
Maximum width (cm)	12.61	2.36	9.40	17.20	7.80
Leaf area (cm²)	308.74	75.18	191.12	460.64	269.52
Cherry characteristics					
Width (mm)	18.95	2.28	15.20	23.30	8.10
Length (mm)	22.23	2.66	16.00	27.10	11.10
Length/width ratio	0.86	0.08	0.68	0.99	0.31
Pulp thickness (mm)	1.46	0.20	1.20	2.00	0.80
Cherry area (mm²)	427.68	97.60	243.20	631.43	388.23
Cherry volume (mm³)	7,742.55	2,001.37	4,405.30	11,438.00	7,032.70
Bean characteristics					
Length (mm)	15.98	1.77	11.50	18.90	7.40
Width (mm)	11.18	1.33	9.10	13.70	4.60
Width/length ratio	0.70	0.07	0.60	0.83	0.23
Thickness (mm)	7.15	0.88	5.30	8.40	3.10
Bean volume (mm³)	2,832.91	866.00	1,166.90	4,408.80	3,241.90

Table 2. Pearson correlation coefficients between morphological traits in *Coffea liberica* (n=12)

Variable 1	Variable 2	Mean±SD (Variable 1)	Mean±SD (Variable 2)	r	p-value
Leaf area (cm²)	Cherry volume (mm³)	308.74±75.18	7,742.55±2,001.37	0.84	0.001**
Leaf area (cm²)	Bean volume (mm³)	308.74±75.18	2,832.91±866.00	0.92	<0.001***
Cherry volume (mm³)	Bean volume (mm³)	7,742.55±2,001.37	2,832.91±866.00	0.70	0.012*
Cherry volume (mm³)	Pulp thickness (mm)	7,742.55±2,001.37	1.46±0.20	0.59	0.043*
Bean volume (mm³)	Pulp thickness (mm)	2,832.91±866.00	1.46±0.20	0.73	0.007**

Note: *p<0.05, **p<0.01, ***p<0.001

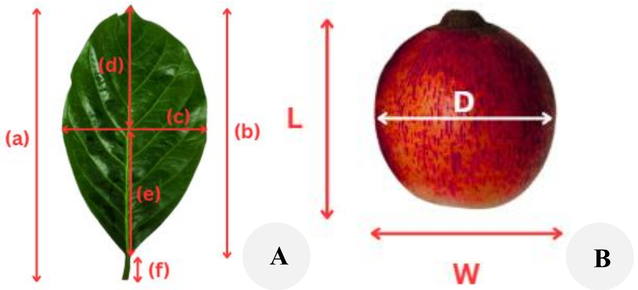

Figure 1. A. Morphological parameters measured from leaf specimens. The measurements included: (a) maximum length (total leaf length from apex to base), (b) blade length (length of the lamina excluding the petiole), (c) maximum width (widest point across the blade), (d) length above maximum width (distance from leaf apex to the point of maximum width), (e) length below maximum width (distance from the point of maximum width to the leaf base), and (f) petiole length (length of the stalk attaching the blade to the stem). B. Morphological parameters measured from coffee cherries. Measurements were obtained using a digital vernier caliper with ±0.01 mm precision. Recorded dimensions included cherry diameter (cross-sectional width at the widest point), length (longitudinal distance from apex to base), and width (lateral distance perpendicular to the length axis)

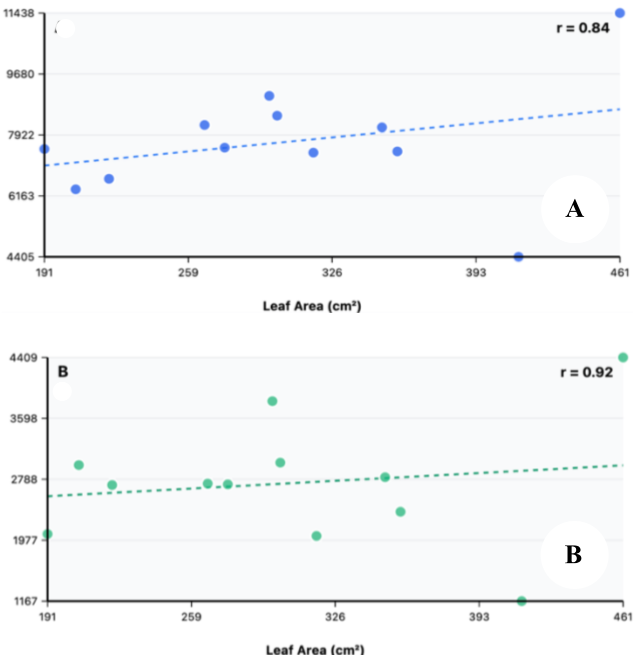

Figure 2. Scatter plots showing correlations between morphological traits in *Coffea liberica* from Batangas, Philippines. A. Relationship between leaf area and cherry volume (r = 0.84, p = 0.001), demonstrating strong positive correlation. B. Relationship between leaf area and bean volume (r = 0.92, p<0.001), showing exceptionally strong positive correlation. Each point represents one of twelve sampled plants (n=12). Dashed lines represent linear regression fits. The strong correlations suggest coordinated morphological development between vegetative and reproductive structures

Discussion

Morphological relationships and coordination

The strong positive correlations between leaf area and both cherry volume (r = 0.84, p = 0.001) and bean volume (r = 0.92, p<0.001) suggest coordinated morphological development in this *C. liberica* population. These relationships align with findings in other coffee species showing connections between vegetative vigor and reproductive success (Degefa et al. 2021). The exceptionally high correlation between leaf area and bean volume indicates that leaf morphology may serve as an indicator of bean size potential, which could be valuable for selection in breeding programs.

Similar morphological coordination has been documented in *C. arabica*, where leaf characteristics correlate with photosynthetic capacity and overall productivity (Alberto et al. 2024; Silva et al. 2025). The relationships observed in this study suggest that *C. liberica* may exhibit comparable developmental integration between vegetative and reproductive structures. However, the mechanisms underlying these correlations require further investigation through physiological studies and multi-site validation.

The moderate correlation between cherry and bean volumes (r = 0.70, p = 0.012) is consistent with established relationships in coffee quality assessment, supporting the principle that larger cherries generally contain larger beans (Bizimungu et al. 2022). This relationship has practical applications for field-based quality evaluation. The correlation between pulp thickness and bean volume (r = 0.73, p = 0.007) suggests that pulp development is more closely linked to seed development than to overall fruit size, which may have implications for processing efficiency and flavor development during fermentation (Osorio Pérez et al. 2022).

Comparison with other coffee species

While direct morphometric comparisons with Philippine *C. liberica* populations are not possible due to lack of existing data, the correlations observed in this study can be contextualized with findings from other coffee species. Studies on *C. arabica* have reported varying degrees of correlation between vegetative and reproductive traits, with correlation coefficients typically ranging from 0.40 to 0.75 for leaf-fruit relationships (Degefa et al. 2021; Yirga et al. 2021). The higher correlations observed in this study (r = 0.84 and 0.92) may indicate stronger developmental coordination in *C. liberica*, though this requires verification through comparative studies with standardized methodologies.

Morphological variation patterns in *C. arabica* and *C. canephora* populations have been extensively documented across different environmental conditions and genetic backgrounds (Bizimungu et al. 2022; Xiao et al. 2024). The 2.4-fold variation in leaf area and 2.6-fold variation in cherry volume observed in this study fall within ranges reported for other coffee species, suggesting that the sampled population exhibits typical intraspecific variation for coffee, implying that the samples used in the study exhibited typical levels of morphological plasticity.

Implications for breeding programs

The strong correlations identified provide potential selection criteria for *C. liberica* breeding programs. Leaf area assessment could serve as an early selection tool for identifying plants with potential for larger bean production, reducing time and resources required in breeding initiatives. However, the limited sample size and single-site nature of this study necessitate validation across multiple locations and larger populations before implementing such selection strategies.

The statistically significant morphological variation in cherry characteristics ($F = 7.820$, $p = 0.014$), while indicating genuine differences among individual plants, occurred within a relatively narrow range compared to reported diversity in other coffee species. This managed variability suggests potential for selection-based improvement while maintaining population uniformity suitable for standardized cultivation. Plants exhibiting favorable combinations of leaf area, cherry size, and bean dimensions could be prioritized for propagation, though selection strategies must consider genetic diversity maintenance.

Understanding morphological relationships can inform cultivation management strategies. Knowledge of leaf-fruit correlations may guide decisions regarding planting density, shade management, and intercropping configurations in agroforestry systems. The morphological characteristics observed support *C. liberica's* documented adaptability to diverse growing conditions (Wafaretta et al. 2023; Hafif et al. 2024).

The relatively consistent pulp thickness despite variation in cherry size suggests standardized processing protocols may be applicable within similar populations. However, it is critical to acknowledge that the morphological relationships observed in this study are from a single location and may be influenced by specific local agro-climatic conditions in Batangas, including soil properties, microclimate, and farm management practices. The observed patterns reflect the interaction between genetic factors and this particular environment, which may differ from other Philippine coffee-growing regions. Multi-site studies incorporating different environmental conditions, elevation gradients, and management systems are essential to distinguish genetically controlled traits from environmentally induced phenotypic plasticity and to develop robust cultivation guidelines applicable across diverse production contexts.

Study limitations and future research directions

This study has important limitations that must be acknowledged. The investigation of twelve plants from a single farm location represents an initial characterization that may not capture the full morphological diversity present across Philippine *C. liberica* populations. The morphological characteristics observed reflect the specific environmental conditions and genetic background of the Batangas location, limiting generalizability to other production regions.

The sample size, while appropriate for initial baseline establishment and correlation exploration, is insufficient for comprehensive population-level conclusions. Seasonal variation in morphological traits was not assessed, as sampling occurred during a single harvest period. Environmental factors specific to this location may have influenced the observed morphological patterns.

Future research should prioritize multi-site morphological evaluations across different agroecological zones, elevation ranges, and management systems throughout the Philippines to establish more comprehensive baseline data. Integration of molecular markers with morphological assessments would provide insights into genetic diversity and population structure. Long-term studies examining morphological relationship stability across seasons and years would strengthen breeding program applications. Investigation of relationships between morphological traits and coffee quality characteristics, including sensory evaluation and chemical composition analysis, would enhance practical applications for specialty coffee development.

In conclusion, this study provides the baseline morphometric data for *C. liberica* in Batangas, Philippines, addressing a knowledge gap in tropical coffee research. The strong correlations observed between the leaf area and both cherry and bean volumes suggest coordinated morphological development that may inform selection criteria for breeding programs and potential tools for quality assessment supporting specialty coffee market development. While the single-site study with twelve plants has important limitations regarding representativeness and generalizability, the morphological relationships identified warrant further investigation across multiple sites and larger populations. The statistically significant variation in cherry characteristics, occurring within a relatively narrow range, indicates opportunities for selection-based improvement while maintaining cultivation uniformity. These findings contribute to understanding *C. liberica* morphology and provide foundation for future research initiatives targeting optimization of production systems, breeding programs, and sustainable cultivation strategies in Philippine coffee agriculture.

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