



Phenotypic and Quality Diversity of Wild Papaya (*Carica papaya* L.) in Coastal Agroecosystems of Ecuador: Implications for Sustainable Use and Conservation

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ABSTRACT

Background: Papaya (*Carica papaya* L.) is one of the most widely cultivated and consumed tropical fruits worldwide. However, its wild genotypes, such as the so-called “monkey papaya,” remain underexplored despite representing valuable reservoirs of genetic diversity. This study aimed to evaluate the phenotypic variability of wild papaya populations from the province of Manabí, Ecuador, as a basis for their conservation and sustainable use.

Methods: A total of 139 individuals were characterized using quantitative descriptors (plant height, fruit weight, pulp thickness, central cavity size, seed count and soluble solids content) and qualitative traits (fruit shape, color and internal cavity appearance).

Result: Statistical analyses revealed significant variation among locations, with Manta populations producing larger fruits, while Junín exhibited the highest soluble solids content. A negative correlation between plant height and fruit size suggested potential trade-offs in resource allocation. Distinct morphotypes were identified, including OCEPP and pear-shaped fruits, particularly in Santa Ana and Sucre.

Key words: *C. papaya*, Fruit shapes, Morphological traits, Tropical fruit, Variability genetic.

INTRODUCTION

Papaya (*Carica papaya* L.) is an economically important tropical and subtropical fruit crop with steadily increasing global production (Carvalho and Renner, 2014; Nantawan *et al.*, 2019). Despite its wide cultivation in more than 50 countries (Saeed *et al.*, 2014), domestication has narrowed genetic diversity in commercial varieties, increasing their vulnerability to pests, diseases and environmental change (Jiménez-Rojas *et al.*, 2025). In contrast, wild papaya populations have continued evolving under natural selective pressures, the leaves have a bioinsecticide effect (Rahayu *et al.*, 2022), retaining alleles associated with tolerance to biotic and abiotic stress, improved nutritional quality and extended post-harvest longevity (Renzi *et al.*, 2022; Heredia-Pech *et al.*, 2025; González-Oviedo *et al.*, 2025). Papaya originated in southern Mexico and Costa Rica and its wild populations extend throughout the tropical and subtropical lowland forests of Mesoamerica (Azad *et al.*, 2014; Chávez-Pesqueira and Núñez-Farfán, 2017). Extensive morphological and molecular assessments conducted in Mexico, Brazil, India and other regions have revealed substantial diversity within wild germplasm, including rare alleles relevant for breeding and conservation (Kim *et al.*, 2002; Matos *et al.*, 2013; Hassan *et al.*, 2022; Leela *et al.*, 2024). These populations commonly consist of fast-growing trees reaching up to 10 m (Ruiz-Gil *et al.*, 2023) and exhibit considerable variation in fruit traits such as size, shape, pulp color and organoleptic attributes (Srivastava *et al.*, 2025; Heredia-Pech *et al.*, 2025). However, despite their recognized importance, the full extent of genetic and

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phenotypic variation across the species' range remains incompletely characterized due to the broad distribution and the presence of understudied populations (Chávez-Pesqueira and Núñez-Farfán, 2016). In coastal Ecuador, specifically in the province of Manabí, wild papaya occurs in scattered populations that show notable morphological heterogeneity, including variation in tree height, petiole color, fruit size and shape (rounded and, in some cases, elongated), number of fruits (more than 60 fruits per tree), mesocarp and endocarp coloration and internal cavity structure patterns consistent with reports from other regions such as Bihar, India (Singh and Kumar, 2010). Yet, these populations remain poorly documented, limiting their integration into conservation strategies and breeding programs. Understanding their phenotypic diversity is therefore essential for identifying traits of agronomic interest and supporting the use of these genetic resources (Zheng *et al.*, 2023). Thus, this study seeks to evaluate the morpho-agronomic variability of wild papaya populations along the coastal gradient of Manabí, Ecuador, providing a basis for conservation planning and for assessing their potential contribution to genetic improvement (Fig 1).

MATERIALS AND METHODS

Sample collection

A total of 139 fruit samples were collected from different papaya trees during 2024 and 2025, representing eight cantons of the Manabí province in Ecuador (Fig 2). Ripe fruits were harvested directly from each tree and stored in a cooler for preservation until processing in the laboratory from the Faculty of Agro-environmental Engineering of the Technical University of Manabí. It is important to note that the selection of trees varied between cantons, because the same number of samples was not found in all sampling sites; therefore, it was not possible to standardize the number of individuals per canton.

Morpho-agronomic characterization

The phenotypic characterization involved the assessment of 11 traits related mainly to fruit morphology and quality. Measurements included longitudinal length (LL), equatorial diameter (ED), the ED/LL ratio (LER), fruit weight (FW), pulp thickness (PT), central cavity diameter (CCD) and the

number of seeds per fruit (NSF). Fruit shape was classified into 13 categories (cacao-shaped, various oval, round and pear-shaped forms differing in peduncular-end morphology and presence of ridges). The central cavity shape was categorized as star-shaped, slightly star-shaped, round, angular, or irregular, following UPOV (2008) descriptors. Fruit and pulp color were recorded and total soluble solids were measured using a digital refractometer (Atago Master M, Atago Co. Ltd., Japan) with a range of 0-32°Brix.

Data analysis

All statistical analyses were conducted in R (R Core Team, 2020). Descriptive statistics for quantitative traits, both overall and by canton, were obtained using the 'dplyr' package (Wickham *et al.*, 2019). ANOVA was performed with the 'aov' function to test for differences among cantons and significant differences ($p < 0.05$) were identified using Tukey's HSD test from the 'agricolae' package (de Mendiburu and de Mendiburu, 2019). Pearson correlation analyses were conducted with 'corrplot' (Wei *et al.*, 2017). PCA visualization was generated using 'Factoextra' (Kassambara and Mundt, 2017). For categorical traits, frequencies and percentages were calculated with dplyr and barplots were produced using ggplot2 (Wickham, 2011).

RESULTS AND DISCUSSION

Morpho-agronomic characterization

The quantitative traits differed significantly among cantons except for plant height (PH) (Table 1). Average pH ranged from 5.33 m in Junín to 8.00 m in Pedernales, with standard deviations of 2.08-3.0 m. Pedernales, sucre and rocafuerte showed the greatest average heights (6.7-8.0 m), while manta (5.50 m) and junín (5.33 m) had the lowest. Fruit size also varied significantly by canton. Longitudinal length (LL) ranged from 11.3 cm (Pedernales) to 21.0 cm (Manta), while equatorial diameter (ED) ranged from 8.3 cm (Sucre) to 37.7 cm (Manta). The LL/ED ratio showed that fruits from manta (1.8) were the most elongated and those from Sucre (0.6) the least. Manta fruits also had the greatest pulp thickness (PT; 22.1 mm) and central cavity diameter (CCD; 74.8 mm), whereas Santa Ana had the smallest PT (14.3 mm) and Junín the smallest CCD (42.9 mm). Fruit weight (FW) followed the same pattern: the heaviest

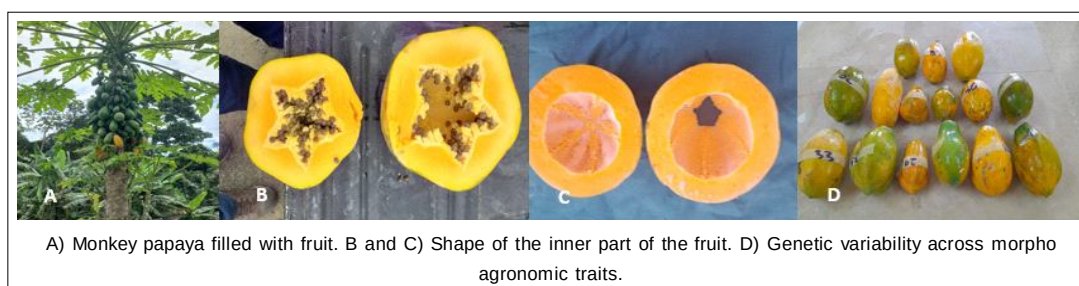


Fig 1: Characteristics of wild *C. papaya* genotypes.

fruits were from manta (773.0 g) and the lightest from santa ana (284.6 g). The number of seeds per fruit (NSF) ranged from 51.3 (Junín) to 123 (Manta).

The PCA (Fig 3) revealed clear morphological differentiation among cantons, with PC1 and PC2 explaining 61.9% of variance. Manta, jipijapa and rocafuerte clustered with larger fruits higher ED, LL, FW, PT, CCD and NSF while santa ana and portoviejo were positioned opposite these size-related traits. Sucre and pedernales associated instead with greater tree height (PH) and more elongated fruits (LER). PC1 was driven mainly by fruit size variables, whereas PH and NSF loaded negatively, indicating trade-offs between vegetative vigor, seed number and fruit development. The full correlation matrix appears in Fig 4 of the 55 fruits analyzed for soluble solids (SS), no significant differences were detected among cantons; however, Jipijapa showed the highest SS (12.2° Brix) and Sucre the lowest (9.08° Brix).

Regarding qualitative variables, 66.7% of the 139 fruits collected were yellow. According to the color of the fruit by

canton, junín presented all yellow fruits (100%), followed by santa ana (89%), manta (83%), pedernales and rocafuerte with 71% and sucre (59%). While green fruits had a more homogeneous distribution, however, they were more frequent in portoviejo (64%) and jipijapa (54%) cantons (Fig 5A). Regarding the pulp, the yellow pulp color was the most frequent with 92.8%. All fruits (100%) from junín, manta and rocafuerte had yellow pulp color. While Portoviejo had the highest quantity of fruits with white pulp (27%), followed by Pedernales (14%) and jipijapa (11%) (Fig 5B).

The OPPE fruit shape was the most frequent (57%), followed by PS (19%) and RS (6%), while all other shapes appeared at ~1%. OPPE was present in all cantons except Manta, with highest frequencies in santa ana (83%), sucre (67%) and jipijapa (61%). Rocafluerte showed the greatest diversity, being the only site with ORPE, OSSR, PSRP, RPR and RRP. Portoviejo uniquely presented EPPE and OSPE, Manta only PSPR and a single CS fruit was found in sucre. For central cavity shape (SCC), star-shaped dominated (46%), followed by slightly star-shaped (21%), irregular (19%), angular (10%) and round (4%). The star type occurred everywhere except pedernales, ranging from 37% (Sucre) to 83% (Manta). Sucre, rocafuerte and jipijapa were the only cantons containing all five SCC types, while the round shape was rare, found only in rocafuerte, jipijapa and sucre.

The observed morphological and fruit quality variability among *C. papaya* populations across the sampled sites is consistent with patterns reported for wild papaya in heterogeneous environments, where phenotypic differentiation reflects the combined influence of genetic background and site-specific climatic, edaphic and geographic conditions (Hernández-Salinas *et al.*, 2022). Comparable levels of variation in plant height, fruit dimensions, pulp thickness and biotic stress tolerance have been documented in other wild genotypes, showing that both heritable traits and environmental heterogeneity play a central role in shaping phenotypic expression (Moore, 2014; Kumar *et al.*, 2015). In terms of physicochemical attributes, differences in soluble solids content among populations align with previous evidence linking sugar

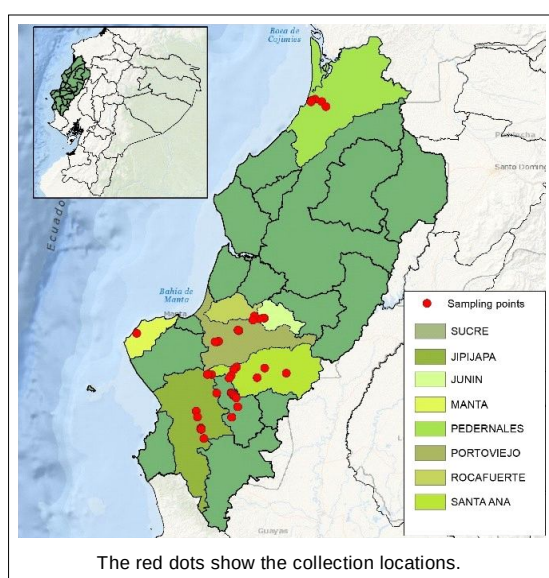


Fig 2: Distribution of the 139 fruit samples of papaya collected within eight cantons of the province of Manabí in Ecuador.

Table 1: Mean, standard deviation (Sd) and range among the 139 papaya fruits collected from eight cantons in Ecuador.

Trait	Unit	Mean	Sd	Min	Max	Significance
PH	m	6.357	2.156	1.5	15	
LL	mm	62.612	59.815	9	200	*
ED	mm	50.378	32.137	15	133.86	*
LER		1.007	0.523	0.359	2.885	*
WF	g	499.771	280.067	1.1	1350	*
PT	mm	17.569	5.097	6	30.63	*
DCC	mm	54.009	15.837	4.1	104.7	*
NSF		86.319	41.888	0	216	*

PH: Plant height; LL: Longitudinal length, ED: Equatorial diameter; LER: Longitudinal/equatorial ratio; WF: Weight of the fruit; PT: Pulp thickness; DCC: Central cavity diameter; NSF: Number of seeds per fruit. Significance at $p > 0.05$.

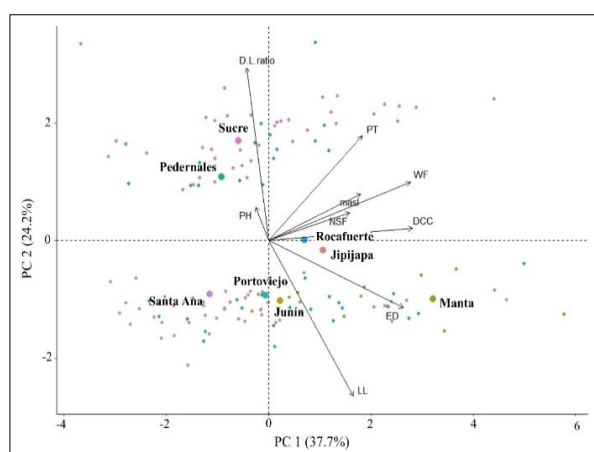


Fig 3: PCA-Biplot analysis based on quantitative traits and collection sites (eight cantons) of the 139 papaya fruits collected within the province of Manabí in Ecuador.

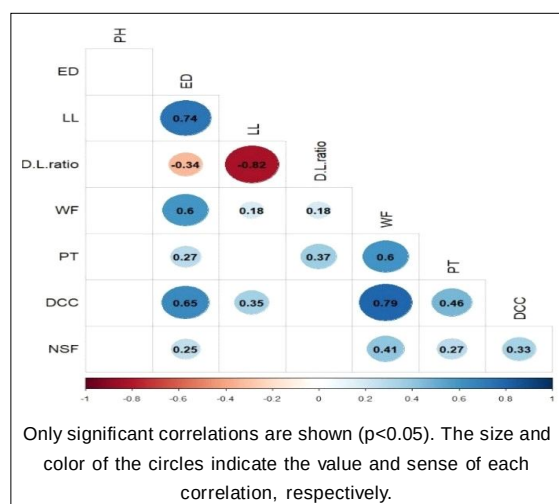


Fig 4: Correlation plot matrix between eight morphological traits for the 139 papaya fruit samples collected in the province of Manabí in Ecuador.

accumulation to water availability and local environmental conditions (Mahouachi and Marrero-Díaz, 2022). These variations are particularly relevant from a commercial perspective, as soluble solids are a key determinant of consumer acceptance and market value (Vargas Tierras *et al.*, 2021). Morphological traits associated with pulp yield, such as cavity diameter and seed number, further differentiated populations. For example, genotypes from Manta exhibited larger central cavities, which may reduce the proportion of edible pulp when compared with populations displaying smaller cavities, a pattern previously associated with site-dependent ecological factors and fruit physiological status (Annegowda and Bhat, 2016). Fruit shape showed pronounced inter-population variability, a characteristic commonly reported in open-pollinated species with seed-based propagation, where cross-pollination patterns and plant sex contribute to high phenotypic diversity (Ávila-Hernández *et al.*, 2023). The prevalence of specific morphotypes, particularly OCEPP, contrasts with the lower frequency of alternative forms and may reflect selective pressures imposed by local market preferences for standardized fruit shapes and sizes (Manshardt, 2012; Maruchi *et al.*, 2008). Conversely, the persistence of less frequent morphotypes in certain locations suggests potential adaptive advantages, such as increased tolerance to environmental stress or disease, potentially mediated by phenotypic plasticity (Potts and Hunter, 2021; Gratani, 2014). These shape-related differences are not merely aesthetic, as fruit form has been shown to influence soluble solids content, firmness and other quality traits relevant for commercialization (PNUD, 2023). Low-frequency morphotypes may therefore result from a combination of genetic constraints and limited market demand (Annegowda and Bhat, 2016; Ovando-Martínez and González-Oviedo, 2020). Color traits also contributed to the differentiation among populations. The dominance of yellow fruit color across most sites is in agreement with reports highlighting its association with higher sweetness and carotenoid content, traits strongly favored by consumers (Chandrika *et al.*, 2003; Laurora *et al.*, 2021).

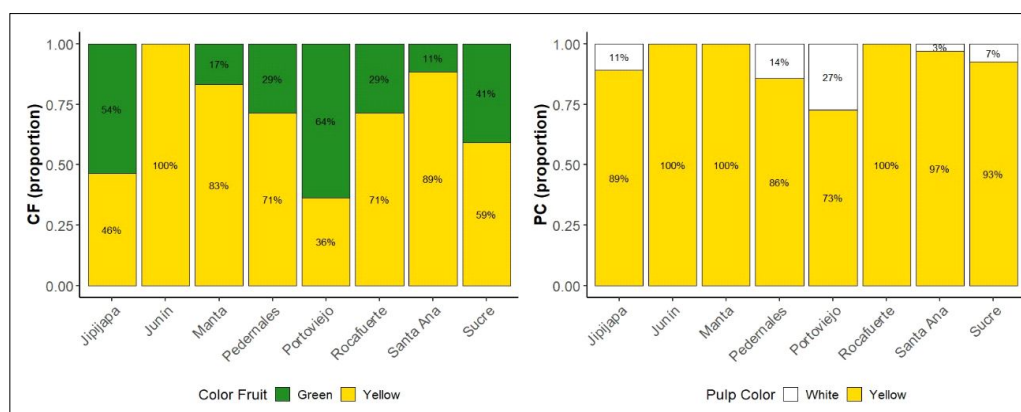


Fig 5: Barplots showing the proportion of fruit (A) and pulp (B) colors by canton of the papaya samples collected.

In contrast, the occurrence of green fruits in specific populations may indicate differences in physiological maturity or shelf life (Patil *et al.*, 2018; Sukorini and Ishartaty, 2025) at harvest or local environmental influences on ripening processes. The limited representation of other color categories suggests the presence of rare or incipient morphotypes, potentially maintained in isolated wild individuals. Similarly, pulp color exhibited marked variability, with yellow pulp being the most frequent, consistent with its recognized nutritional value and consumer preference (Aryal and Ming, 2014; Chung *et al.*, 2023; Schweiggert *et al.*, 2011). Alternative pulp hues likely reflect underlying genetic diversity or environmentally driven modulation of pigment biosynthesis pathways, as reported in other tropical fruit species (Oziegbe *et al.*, 2015). The variation in central cavity shape among populations appears to be influenced by both genetic structure and local environmental conditions characteristic of coastal habitats. The predominance of star-shaped cavities across sites may indicate a functional advantage related to internal fruit architecture and seed arrangement, as previously proposed by Tan *et al.* (2021). Overall, the comparative patterns observed across populations underscore the strong interaction between environmental gradients and genetic diversity in determining fruit morphology and quality in wild *C. papaya* populations.

CONCLUSION

Wild genotypes of *C. papaya* show substantial genetic and phenotypic variability, expressed in diverse morphological and fruit quality traits across localities. This diversity provides valuable traits for consumption and crop improvement, reinforcing the importance of conserving these genetic resources. Ensuring both *in situ* and *ex situ* conservation is essential to safeguard their contribution to food security, ecological resilience and the sustainability of tropical fruit production systems.

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Disclaimers

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Informed consent

There were no animal trials or samples.

Conflict of interest

The authors declare that there are no conflicts of interest regarding the publication of this article. No funding or sponsorship influenced the design of the study, data collection, analysis, decision to publish, or preparation of the manuscript.

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