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Variability in Morphometric and Agronomic Traits of Native Bean Seeds (*Phaseolus vulgaris* L.) and Edaphoclimatic Characterization

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ABSTRACT

Background: Farmers conserve bean germplasm due to its importance in nutrition despite recent socioeconomic changes in their communities. The objective of the study was to analyze the edaphoclimatic conditions, morphometric and agronomic characters in seeds of bean varieties.

Methods: Seeds of native varieties were collected in the Las Montañas region, Veracruz, Mexico, with data on temperature, precipitation and soil properties were extracted. The native materials were grown together with the Negro INIFAP variety and the commercial grains Michigan and Pinto. Qualitative variables (frequency and correspondence analysis) and quantitative variables were evaluated, the latter related to the plant, as well as dimensions and weight of the seed, following a complete and completely randomized block design, respectively.

Result: Native varieties develop in ranges of 18.4 to 25.5°C and between 1 827 to 2 610 mm of precipitation and soils with average values of organic matter and pH of 5.89-7.04. Differences were present in the qualitative characters and in the number of seeds per pod (NSE), weight of one hundred seeds (WHSE) and seed dimensions ($p \leq 0.01$). The Amarillo milpa variety reached the highest NSE with 7.33 and Pinto stood out over the WHSE (33.41 g). The native varieties are classified as small (<25 g 100 seeds), characteristic of the Mesoamerican race. In conclusion, the diversity in qualitative and quantitative characters in bean varieties reflects adaptations to contrasting edaphoclimatic conditions, which has implications for genetic improvement, food security and sustainability.

Key words: Bean, Diversity, Morpho-agronomic characterization, Morphology, Precipitation, Temperature.

INTRODUCTION

The common bean (*Phaseolus vulgaris* L.) is a leguminous plant of the Fabaceae family, whose cultivation originated in Mesoamerica and it was between 5000 and 2000 years BC that it was domesticated in what is now known as Mexico, Central America and the Andes (Hernández-López *et al*., 2013). In the area of domestication, genotypes originated that through crosses manifested outstanding phenotypic variations, including seed size and weight (Singh *et al*., 1991; Sadohara *et al*., 2022), resulting from the associated combination of the diversity composed of the presence of native, wild and improved varieties and from the product of genetic introgression (Almeida *et al*., 2020; Catarcione *et al*., 2023).

The seed of the common bean constitutes the most important food grain for human consumption worldwide (De Ron and Rodiño, 2024). In Mexico, its consumption represents up to 36% of the daily protein intake (Anaya-López *et al*., 2021) and it provides macro and microelements such as Fe and Zn (Espinoza-García *et al*., 2016; Jan *et al*., 2021). Due to its nutritional importance, the common bean is cultivated by 570,000 producers in Mexico, where it generates 382,000 permanent jobs, with a production of 17 billion Mexican pesos, highlighting the states of Zacatecas, Sinaloa and Nayarit, which together produce 50% of the national production (SADER, 2022; SIAP, 2024).

Although there is a wide range of improved bean seeds (SADER-SNICS, 2022), it is necessary to conserve, maintain and characterize the native varieties that are still cultivated in agricultural regions of Mexico, this can

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contribute to the identification of genotypes with desirable characteristics to be incorporated into an improvement and genetic conservation program (Saburido and Herrera, 2015; Ayala-Garay *et al*., 2021). In addition, this strategy allows the approach of research to address the problems of genetic erosion and the search for materials resilient to climate change (Maxim *et al*., 2016; Catarcione *et al*., 2023). Due to recent socio-economic changes in the rural communities where native bean varieties are currently cultivated, the morpho-agronomic and edaphoclimatic prospecting where these native bean materials are cultivated represents a strategy to ensure self-consumption of low income families (García-Narváez *et al*., 2020).

The edaphoclimatic distribution areas for the proper development of bean cultivation are found in areas with an average temperature between 15 and 20°C, with a minimum and maximum daily temperature of 10 and 27°C, respectively, as well as in areas with average precipitation but without excess moisture, in addition to soils with light texture and good drainage (FAO, 2022). However, native bean varieties are cultivated in marginal areas with low-input production systems, which possess valuable adaptation traits that must be characterized for their management and conservation (Negri *et al*., 2009).

In the central part of the state of Veracruz, in the region known as Las Montañas, native and creole bean varieties are preserved and their edaphoclimatic conditions in which they develop must be known and their morphometric and agronomic characters must be analyzed to assess the diversity of bean phenotypes in this central region of Veracruz, under the context that native beans stand out for their adaptability to diverse edaphoclimatic conditions and their broad capacity to offer a variety of phenotypes that in the future will be crucial for food security and agricultural sustainability. Based on the above, the objective of the study was to analyze the morphometric, agronomic and edaphoclimatic characteristics of seeds of native bean varieties in the Las Montañas region, Veracruz, Mexico.

MATERIALS AND METHODS

Collection of bean varieties, establishment, crop management and experimental design

In September 2023, seed collections of bean varieties were carried out through field trips in three municipalities of the Las Montañas region, Veracruz, Mexico, which were classified into six bean varieties: Amarillo milpa, Negro milpa, Tlalchete, Güero Amatlán, Negro Amatlán and Noche buena beans (Fig 1). From these, passport data were collected, which included information on the donor, municipality, locality, biological condition, source of acquisition and the consumptive use of the collected varieties. The geographic location of these collection sites was geo-referenced using the Apps and Tools, GPS v. 5.09 application for Android, corroborated with Google Earth Pro® and plotted in QGIS® software (QGIS Development, 2021) (Fig 1).

The native bean varieties were established as a crop in the Experimental Field of the Facultad de Ciencias Biológicas y Agropecuarias, Orizaba-Córdoba region, Universidad Veracruzana, located in the municipality of Amatlán de los Reyes, at coordinates 18.75°N, 96.75°W and at an altitude of 731 m (Fig 1) and has a semi-warm humid climate (A)C(m)(f) (García, 2004), with an average annual temperature of 22.9°C and precipitation of 2 372 mm, based on the historical series 1950-2019 (Harris *et al*.,

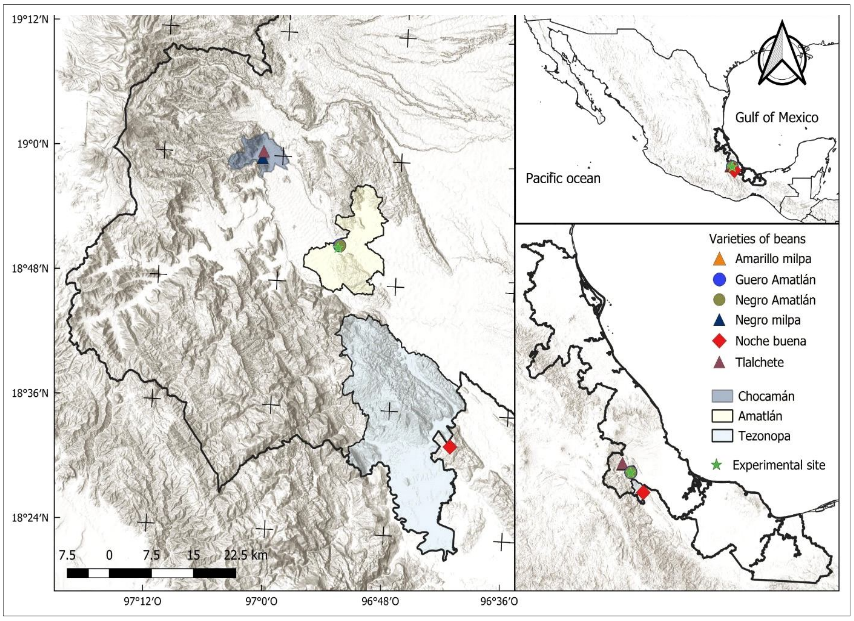

Fig 1: Collection sites of native bean (*Phaseolus vulgaris* L) varieties in three municipalities of the Las Montañas region, Veracruz, Mexico and cultivated in Amatlán de los Reyes, Veracruz.

2020). Regarding the soil of the experimental plot where the crop was developed, it was classified as a vertisol type (INEGI, 2024), with a clay loam texture, pH of 5.4, organic matter of 3.77%, low nitrogen content (0.0024%), medium K content (183 mg kg^{-1}) and Ca (7.4 cmol (+) kg^{-1}) and high phosphorus (P= 68.82 mg kg^{-1}) and magnesium (Mg= 4.81 cmol(+) kg^{-1}) content.

The experimental plot soil was prepared for sowing by manual weeding, soil decompaction with a subsoiler and mechanical furrowing. The experimental plot consisted of two rows per variety, which were sown on both sides of these (ribs), resulting in four 5 m long rows. This design corresponded to a randomized complete block design with five replications. For comparative purposes and as experimental controls, the bean varieties Negro Michigan, Pinto and Negro INIFAP were also cultivated. Data were recorded from the measurement of five plants from the central rows, avoiding the border rows and the headers.

Sowing was carried out on September 12 of 2023, depositing three seeds per hole, with a separation of 30 cm between plants. Weed control was done manually and two fertilizations were carried out, at 20 and 40 days after sowing (DAS) with 10 g of diammonium phosphate and Blaukorn®, respectively. The Amarillo and Negro milpa varieties were provided with a stake due to their indeterminate growth habit. On December 14 of 2023, when the plants showed physiological maturity, were pulled and dried for 40 days in the shade and then manual threshing was performed.

Morpho-agronomic characterization of the seed

When the native, commercial and improved bean seeds had a moisture content of 14% (López *et al*., 2012), their qualitative variables were evaluated: seed shape in longitudinal section (SSLS); seed shape in cross-section (SSCS); seed colors (COLS); number of seed colors (NSC); distribution of the secondary color (DSSC); luster of the testa (LTES). A frequency table was constructed with the data, to which a correspondence analysis was applied with the objective of evaluating the relationship between the qualitative variables in a multidimensional space; the categories (variables) were related by the combination in the similarity of the frequencies, indicating a similarity or distance between the evaluated characters; this analysis was developed in the InfoStat software (Di Rienzo *et al*., 2022).

The quantitative variables evaluated were: number of pods (NPODS), number of seeds per pod (NSPOD), weight of one hundred seeds (WHSE in g) and yield per plant (YPLAN in g); seed dimensions in mm: length (SLEN), width (SWID) and thickness (STHIC). In addition, the seed length/width index (SLWI), the seed length/thickness index (SLTI) and the seed width/thickness index (SWTI) were estimated. Data collection was carried out in a completely randomized experimental design with three replications (50 seeds per replication). The data were subjected to a normality and homogeneity of variances test using the Shapiro-Wilks and Levene tests, respectively, with a 95% confidence level. The NPODS and YPLAN variables were transformed through the $\sqrt{x}$ function to meet the statistical assumptions and to facilitate the understanding of the results, the data were retransformed to their original value. The variables were subjected to an analysis of variance (ANOVA) and a Tukey's mean comparison test ($p\leq0.05$).

Edaphoclimatic characterization

To know the climatic and edaphic conditions in the localities where the bean varieties were collected in the three municipalities of central Veracruz, a database was designed in Excel® software that contained the geographic coordinates of each collection site, which was incorporated as a point layer in the QGIS® v. 3.28 software. In the same software, eight climatic variables were incorporated in raster format: mean annual temperature in °C (Bio1), maximum temperature of the warmest month (Bio5), mean temperature of the wettest quarter (Bio8), mean temperature of the driest quarter (Bio9), mean temperature of the warmest quarter (Bio10), mean temperature of the coldest quarter (Bio11), annual precipitation (Bio12), precipitation of the wettest month in mm (Bio13), precipitation of the driest month in mm (Bio14), precipitation of the warmest quarter (Bio18) and precipitation of the coldest quarter in mm (Bio19), which were obtained from the Worldclim database for the period 1970-2000 (Fick and Hijmans, 2017).

In addition to the above, eight edaphic variables were incorporated: pH, Na (cmol L^{-1}), EC (dS m^{-1}), organic matter (OM, %), potassium (K, cmol L^{-1}), calcium (Ca, cmol L^{-1}), magnesium (Mg, cmol L^{-1}) and organic carbon (OC, kg m^{-2}) (Cruz-Cárdenas *et al*., 2014). The edaphoclimatic information was obtained using the Point Sampling Tools® tool in the QGIS® v. 3.28 software, which extracts the values of the climatic and edaphic variables from the coordinates of the bean collection sites. This type of analysis has been carried out to characterize edaphoclimatic aspects and ecological niche distribution in crops such as sugarcane, apple chili, mango, kiwi and maize (Serna-Lagunes *et al*., 2020; Hernández-Salinas *et al*., 2023; López-Páez *et al*., 2023; Cebada-Merino *et al*., 2024; Zamudio-Galo *et al*., 2024).

RESULTS AND DISCUSSION

Description of the management of native varieties

The bean materials were found at altitudes ranging from 431 to 1 644 masl; that is, a difference of 1 233 m in altitude, between the Noche buena variety and those from Chocamán, Veracruz. This agrees with Miranda (1967), who reported wild and domesticated varieties of *P. vulgaris* between 500 and 1 800 masl in the Sierra Madre Occidental. The native bean varieties presented a biological condition called traditional cultivar, that is, they are considered creole and/or native varieties and were frequently observed in small plots managed as monocultures or associated with maize due to their climbing habit, such as the Noche buena, Negro milpa and Amarillo milpa varieties. In Mexico, the maize-bean association is common and it is possible to intercrop with other crops such as banana, coffee and sugarcane; mainly in agricultural farms with crop diversity (Ngoya *et al*., 2023). The main reported use of beans in the study was for self-consumption, although the harvest of the Amatlán de los Reyes varieties is commercialized in the local market (Table 1). It is noteworthy that farmers maintain the tradition of selecting seeds as germplasm to be used in the sowing of the next agricultural cycle. According to INEGI (2016), it was found that the varieties are cultivated under three land uses: 1) permanent rainfed agriculture (Chocamán), 2) semi-permanent rainfed agriculture (Amatlán de los Reyes) and 3) secondary arboreal vegetation of high evergreen rainforest for the municipality of Tezonapa, Veracruz.

Description of edaphoclimatic conditions

Environmental conditions affect the rate of development and agronomic behavior of bean cultivation (Sozen *et al*., 2018; Maqueira-López *et al*., 2021). In this regard, it was found that bean varieties are cultivated under a semi-warm humid (A)C(m)(f), (A)C(m) and warm humid (Am) climate (García, 2004), which comprise ranges between 18.4 to 25.5°C of mean annual temperature (Table 2) and maximum temperatures of the warmest and coldest month with 27.8 to 35.2°C and 8.36 to 16.1°C, respectively. Based on the above, the environmental interval where the bean expresses its productive potential is between 15 to 21°C, since sites with frost are not suitable for the species, while sites with conditions <4°C, are detrimental to germination, flowering and fruiting, while seed formation is affected when temperatures >35°C occur (FAO, 2001). In this sense, the bean varieties in the present study show tolerance to the climatic extremes where they are cultivated, which can generate adaptations and evolve towards necessary characters that tolerate those extreme conditions.

Regarding humidity, the field records where the collected bean varieties were cultivated ranged between 1 827 to 2 610 mm of annual precipitation, while in the wettest month and the warmest month precipitation ranged between 338 to 526 mm and 38.67 mm, respectively (Table 2). This environmental condition allows the bean crop to develop under rainfed conditions; that is, with the residual moisture produced by the rains (Ayala *et al*., 2021). One aspect that should be highlighted is that the precipitation range was wider than that reported for the species (Table 2), since the recommended optimum for sowing this species is between 1 600 to 2 500 mm, since precipitation below 1 000 mm and above 3 000 mm limit development and yield (Ramírez-Jaramillo *et al*., 2023). For good crop development, a balance is required between the distribution and availability of rainfall in relation to the phenological cycle in the flowering, pod formation and grain filling phases (Ugalde-Acosta *et al*., 2005), due to the

Table 1: Passport information of bean varieties in Las Montañas, Veracruz, Mexico.

Donor	Common name	Municipality	Location	Altitudemasl	Use	Climate	Soil
J.L. Del Rosario M.	Amarillo milpa	Chocamán	Zonotzintla	1644	A	(A)C(m)(f)	Humic andosol
J.L. Del Rosario M.	Negro milpa	Chocamán	Zonotzintla	1644	A	(A)C(m)(f)	Humic andosol
J.L. Del Rosario M.	Tlalchete	Chocamán	Chocamán	1367	A	(A)C(m)(f)	Humic andosol
M. Becerra Sainz	Güero Amatlán	Amatlán	Peñuela	732	A/V	(A)C(m)	Chromic vertisol
M. Sierra Valerdi	Negro Amatlán	Amatlán	Peñuela	732	A/V	(A)C(m)	Chromic vertisol
X. Santos Ramos	Noche buena	Tezonapa	Cerro Alto	431	A	Am	Leptosol

Table 2: Climatic conditions where bean varieties are cultivated in Las Montañas, Veracruz.

Bean varieties	BIO1	BIO5	BIO6	BIO8	BIO9	BIO10	BIO11	BIO12	BIO13	BIO14
Negro milpa	18.4	27.8	8.4	19.7	16.4	20.6	15.5	1827.0	338.0	39.0
Amarillo milpa	18.4	27.8	8.4	19.7	16.4	20.6	15.5	1827.0	338.0	39.0
Tlalchete	19.0	28.5	8.8	20.3	16.93	21.2	16.0	1693.0	314.0	36.0
Negro Amatlán	21.7	31.6	11.7	23.3	19.6	24.0	18.7	1681.0	312.0	41.0
Güero Amatlán	21.7	31.6	11.7	23.3	19.6	24.0	18.7	1681.0	312.0	41.0
Noche buena	25.6	35.2	16.1	26.9	23.1	28.2	22.2	2612.0	526.0	36.0
Maximum value	25.6	35.2	16.1	26.9	23.1	28.2	22.2	2612.0	526.0	41.0
Minimum value	18.4	27.8	8.4	19.7	16.4	20.6	15.5	1681.0	312.0	36.0
Average	20.8	30.4	10.8	22.2	18.7	23.1	17.8	1886.8	356.7	38.7

BIO1= Mean annual temperature; BIO5= Maximum temperature of the warmest month; BIO6= Maximum temperature of the coldest month; BIO8= Mean temperature of the wettest quarter; BIO9= Mean temperature of the driest quarter; BIO10= Mean temperature of the warmest quarter; BIO11= Mean temperature of the coldest quarter; BIO12= Annual precipitation; BIO13= Precipitation of the wettest month; BIO14= Precipitation of the driest month.

demand for assimilates required by the reproductive structures (Manjeru *et al*., 2007; Tosquy-Valle *et al*., 2014). However, the bean varieties studied showed their tolerance and ability to survive short periods of drought, which could increase the proline content generated by water stress, making it a resilient and adaptable crop to climate change (Batool *et al*., 2023), so its management and conservation is necessary.

Regarding the edaphic characterization, the medium organic matter contents (1.98 to 2.83%), with moderately acidic to neutral pH (5.89-7.04), as well as variable concentrations and amounts of minerals such as Ca (0.49 to 0.69 cmol L^{-1}), OC (6.16 to 9.31 kg m^{-2}) and Na (0.13 to 0.24 cmol L^{-1}), present in the sites where the bean varieties are cultivated (Table 3). The edaphic conditions are within the favorable ranges for crop development, since the optimal acidity for cultivation ranges between 5.5 to 6.5 (Ramírez *et al*., 2023); while the nitrogen and phosphorus contents are adequate for production (Dorcinvil *et al*., 2010), this shows the species ability to adapt to a wide variety of edaphic conditions. However, it is likely that the high soil acidity (>5) has negative effects on the maturity, growth and yield of the bean varieties, reducing grain yield by 26% due to this factor (Legesse *et al*., 2013). Similarly, reproductive fertility decreases in the plant due to low nutritional quality, which causes bean plants to develop thin stems and low seed weight, due to a decrease in Zn (Rocha *et al*., 2020). In this regard, in plant breeding programs, some limiting parameters such as low soil fertility and acidity are taken as a reference; in this way, experimental genotypes with adaptation to strongly acidic soils (pH= 4.67) and low OM content (0.86%) are reported (Tosquy-Valle *et al*., 2020); therefore, the materials evaluated in this study are considered feasible to be incorporated into a regional genetic diversity management and conservation program, as well as to increase exploration efforts for other bean varieties in other municipalities.

Qualitative characteristics of bean varieties

Qualitative characteristics have an impact on the *in situ* conservation of bean diversity, such as the shape, color and size of the seed; meanwhile, the preference for varieties is linked to culture and geographic area (Stoilova *et al*., 2013; García-Narváez *et al*., 2020). It was observed that the native varieties stand out for their seed shape in longitudinal section, which is reniform (50%) and elliptical (33.33%); flattened (50%) with respect to the seed shape in cross-section; seeds of a single color on the testa (83.33%) and classified as black, yellow, sulfur and red, in addition to different color of the hilum on the testa (100%). It is noteworthy that the Negro and Amarillo milpa varieties are characterized by a high luster on the seed, while the rest, including the commercial ones, report medium or absent luster (Table 4).

The importance of seed coat color is a useful characteristic to guide plant breeders on the morphological traits that need to be improved to increase productivity and ensure their adoption by farmers and consumers is viable (Loko *et al*., 2018). In this sense, the ecotypes based on testa color in the *P. vulgaris* varieties present in the three municipalities studied were yellow, red, cream, olive, purple, black, brown, gray and their different shades (Jan *et al*., 2021), representing different bean morphotypes (Fig 2).

The correspondence analysis indicated that the qualitative characters evaluated in the bean varieties presented an accumulated variation of 58%. The Negro milpa variety presented the qualitative characteristics with the greatest dissimilarity, while the Pinto bean presented yellow-brown colorations that stand out compared to the other bean varieties; it is important to highlight the Güero Amatlán variety with brown coloration and narrow elliptical shape and which differs from the other varieties. The Negro Amatlán, Amarillo Milpa, Michigan and Noche buena bean varieties presented similarity due to seeds with yellow and black coloration (Fig 3).

Quantitative characteristics in bean varieties

Significant differences were found in the variables, number of seeds per pod and 100-seed weight ($p \leq 0.01$) in the bean varieties. The coefficients of variation were between 11.40 and 41.03% (Table 5), an interval that is considered an excellent indicator of the existing variability between

Table 3: Soil properties of the bean collection sites in the Las Montañas region, Veracruz.

Bean varieties	pH	OM	Mg	K	Ca	OC	Na	EC
Negro milpa	5.95	2.6	0.21	0.05	0.52	8.51	0.13	0.13
Amarillo milpa	5.95	2.6	0.21	0.05	0.52	8.51	0.13	0.13
Tlalchete	5.89	2.7	0.20	0.05	0.49	8.56	0.13	0.13
Negro Amatlán	6.26	2.8	0.25	0.05	0.63	9.31	0.17	0.13
Güero Amatlán	6.26	2.8	0.25	0.05	0.63	9.31	0.17	0.13
Noche buena	7.04	1.9	0.30	0.04	0.69	6.16	0.24	0.13
Maximum value	7.04	2.8	0.30	0.05	0.69	9.31	0.24	0.13
Minimum value	5.89	1.9	0.20	0.04	0.49	6.16	0.13	0.13
Average	6.23	2.6	0.24	0.05	0.58	8.39	0.16	0.13

OM= Organic matter (%); Mg= Magnesium (cmol L^{-1}); K= Potassium (cmol L^{-1}); Ca= Calcium (cmol L^{-1}); OC= Organic carbon (kg m^{-2}); Na= Sodium (cmol L^{-1}); EC= Electrical conductivity (dS m^{-1}).

Table 4: Frequency of qualitative characters of bean seeds in Las Montañas, Veracruz.

Character	Variant	Absolute frecuency	Relative frecuency (%)
Seed shape in the longitudinal section	Circular	1	16.67
	Elliptical	2	33.33
	Reniform	3	50.00
Seed form in cross section	Flattened	3	50.00
	Narrow elliptical	1	16.67
	Average elliptical	1	16.67
	Wide elliptical	1	16.67
Type of seed	Yellow	1	16.67
	Sulfur	1	16.67
	Black	2	33.33
	Red	1	16.67
	None of the above	1	16.67
Seed colors number	One	5	83.33
	Two	1	16.67
Main seed color	Yellow	1	16.67
	Red	1	16.67
	Brown	2	33.33
	Black	2	33.33
Secondary seed color	Present	1	16.67
	Absent	5	83.33
Secondary color distribution	In the entire seed	1	16.67
	Absent	5	83.33
Luster of the testa	Absent or very slight	1	16.67
	Medium	2	33.33
	A lot	3	50.00
Crown color of the hilum	The same color as the testa	0	0
	Different color than the testa	6	100.00

Table 5: Analysis of variance applied to morpho-agronomic characters of bean varieties from the Las Montañas region, Veracruz, Mexico.

Source of variation	GL	NPODS	NSPOD	WHSE	YPLAN
Varieties	7	7.18	2.68**	252.00**	1.10
Block	2	0.06	0.25	9.25	0.27
Error	81	0.38	0.62	6.36	1.02
CV		37.07	12.86	11.40	41.03

CV= Coefficient of variation; GL= Degrees of freedom; NPODS= Number of pods per plant; NSPOD= Number of seeds per pod; WHSE= Weight of one hundred seeds; YPLAN= Yield per plant.

Fig 2: Qualitative traits in the varieties of native, commercial and improved bean seeds.

populations and is an important tool in plant breeding (Franco and Hidalgo, 2003; Arteaga *et al*., 2019). High values were found for the NPODS and YPLAN traits and although they did not show significant differences (Table 5), these are sources of genetic variability that can be selected to develop varieties with desirable characteristics and conserve them through the promotion of their cultivation.

Variability was found among the accessions, with highly significant differences for all seed dimensions and indices (Table 6, p≤0.01). In this regard, seed length, width and thickness are morphological traits of importance due to their discriminatory power among bean populations (Espinosa-Pérez *et al*., 2015). Regarding the coefficients of variation, they were between 2.54 and 6.59, which demonstrates, on the one hand, the reliability of the data because the sample size reduced the error, as well as the normality and homogeneity (Castillo, 2007).

Comparison of means in morpho-agronomic variables of bean seeds

The Pinto variety stood out in seed length with 12.77±0.18 mm (Fig 4a), followed by the native variety Noche buena (11.10±0.23 mm), while Negro milpa, Amarillo milpa, Tlalchete, Negro and Güero Amatlán varied from 9.68 to 10.43 mm, dimensions similar to those found in the varieties from Costa Rica named as Mantequilla, Nica, Revuelto, Sesenteno, Turrialba and Vaina Blanca (Oreamuno-Fonseca *et al*., 2023); likewise, they coincide with the length of genotypes from the western Himalayas of Mesoamerican origin (12.97±2.63 mm) (Jan *et al*., 2021).

Likewise, the Pinto variety was characterized by a greater dimension in seed width with 7.35±0.15 mm, followed by Güero Amatlán, Negro Amatlán, Negro INIFAP, Negro milpa and Tlalchete with 6.35±0.16, 6.46±0.12, 6.34±0.17, 6.49±0.15 and 6.35±0.11 mm, respectively (Fig 4b),

Seed shape in longitudinal section (SSLS); Seed shape in cross-section (SSCS); Seed colors (COLS); Number of seed colors (NSC); Distribution of the secondary color (DSSC); Luster of the testa (LTES).

Fig 3: Correspondence analysis relating the qualitative characteristics of seeds of native, commercial and improved bean varieties.

Table 6: Analysis of variance in seed characters of native and commercial bean varieties from three municipalities in the Las Montañas region, Veracruz, Mexico.

Source of variation	GL	SLEN	SWID	STHIC	SLWI	SLTI	SWTI
Varieties	7	13.15**	2.49**	1.77**	0.16**	0.23**	0.10**
Repetition	2	0.03	0.02	0.02	0.02	0.02	0.12
Error	109	0.07	0.03	0.07	0.01	0.02	0.0039
CV		2.54	2.85	5.57	4.78	6.31	6.59

CV= Coefficient of variation; GL= Degrees of freedom; SLEN= Seed length; SWID= Seed width in cross-section; STHIC= Seed thickness; SLWI= Seed length/width index; SLTI= Seed length/thickness index; SWTI= Seed width/thickness index.

this group had lower values compared to the Creole Negro (6.60 mm) collected in the Hopelchén region in the state of Campeche, Mexico Mex-Álvarez *et al*. (2021) and advanced lines (6.50±0.70 mm) from Peru (Pumalpa *et al*., 2020). The varieties studied were superior (6.20±0.10 mm) to those reported in 57 creole bean accessions collected in the central region of the Republic of Benin (Loko *et al*., 2018).

Also, The Pinto bean seeds had the highest value in their thickness (5.41±0.16 mm), while lower values were found in the Tlalchete variety at 4.30±0.09 mm (Fig 4c); however, the difference between these is reduced since in other reports such as that of Sinkoviè *et al*. (2019) in which germplasm from Slovenia (953 accessions) presents thickness values ranging from 4.24 to 9.56 mm.

The comparison of means (Table 7) showed that for the case of the estimated indices directly related to seed shape, the maximum seed length/width index was observed in the Noche buena variety with 1.88±0.14. In this sense, all varieties presented values greater than 1.5, indicating that they have an elongated shape (Oreamuno-Fonseca *et al*., 2023). The highest value in the seed width/thickness index which gives a reference on the cylindrical shape of the seeds was presented in the Tlalchete variety with 1.49±0.04. The results of both indices are similar to those presented as an average of 953 accessions of *P. vulgaris* in which values of 1.69±0.28 and 1.24±0.16 are reported, respectively (Sinkoviè *et al*., 2019). Regarding the seed length/thickness index, the highest value was recorded in the Tlalchete variety and the lowest in the Amarillo and Negro milpa varieties with 2.41±0.05, 2.05±0.10 and 2.05±0.03, respectively.

The number of pods was similar across the bean varieties, ranging from 15.60±0.58 to 28.62±1.12, values that are relatively low compared to the French bean variety, which reported between 59.2±9.76 and 71.0±9.07 under different population densities (Sundar and Lal, 2022). Additionally, the Amarillo milpa bean variety reached the

Table 7: Comparison of means of morpho–agronomic characters of nine bean varieties.

Varieties of bean	SLWI	SLTI	SWTI	NPODS	NSPOD	WHSE (g)	YPLAN (g)
Negro milpa	1.62±0.01cd	2.05±0.03e	1.27±0.02de	25.60±0.92a	6.32±1.16b	21.12±3.12b	26.73±1.93a
Amarillo milpa	1.59±0.04cd	2.05±0.10e	1.29±0.05cde	15.60±0.58a	7.33±0.58a	18.80±2.48b	19.10±0.96a
Tlalchete	1.63±0.02cd	2.41±0.05a	1.49±0.04a	28.20±10.00a	6.14±0.98b	18.84±1.46b	26.83±0.69a
Negro Amatlán	1.60±0.03cd	2.34±0.12ab	1.47±0.07ab	25.00±0.62a	6.20±0.41b	19.24±1.35b	22.37±0.32a
Güero Amatlán	1.65±0.04bc	2.28±0.11abc	1.4±0.05abc	20.07±0.81a	6.19±0.91b	20.74±2.27b	22.66±1.14a
Noche buena	1.88±0.14a	2.25±0.14bcd	1.2±0.12e	SD	SD	SD	SD
Negro INIFAP	1.56±0.02cd	2.13±0.10cde	1.37±0.05bcd	28.62±1.12a	6.49±0.65b	19.19±1.60b	29.16±1.44a
Michigan	1.54±0.16d	2.11±0.30de	1.39±0.19abc	25.40±0.92a	5.92±0.54b	19.88±3.37b	21.07±0.98a
Pinto	1.73±0.03b	2.34±0.07ab	1.36±0.05cd	21.16±0.25a	5.03±0.71c	33.41±3.08a	24.80±0.74a
Mean	1.64	2.22	1.36	23.71	6.20	21.40	24.09

SLWI= Seed length/width index; SLTI= Seed length/thickness index; SWTI= Seed width/thickness index; NPODS= Number of pods per plant; NSPOD= Number of seeds per pod; WHSE= Weight of one hundred seeds; YPLAN= Yield per plant. SD= Without data.

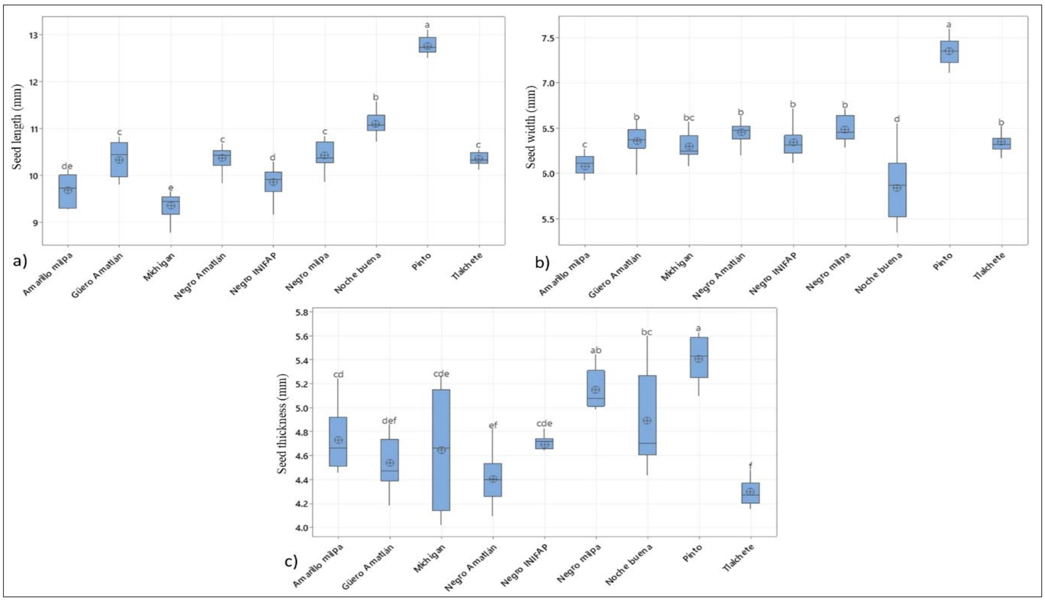

Fig 4: Seed dimensions of nine bean varieties, a) Length, b) Width and c) Thickness.

highest number of seeds per pod, in this case with 7.33, higher than the other varieties. Regarding the weight of one hundred seeds, the Pinto variety stands out, with a value of 33.41 g, lower than the Pinto Saltillo (40.99±1.99 g) cultivated in its area of adaptation (Corzo-Rios *et al*., 2020), which is probably due to the high values in the parameters of seed length, width and thickness, For the native varieties and the Michigan commercial grain, these presented a weight of 18.80 to 20.74 g (Table 7). According to the above, small seeds (<25 g per 100 seeds) and the presence of 6 to 8 seeds per pod indicate a strong resemblance of the varieties to the Mesoamerican race (Singh *et al*., 1991). Likewise, the seed weight values (WHSE) were lower than the advanced and commercial black bean lines (21 to 26 g) generated by the National Institute of Forestry, Agricultural and Livestock Research under acidic soil conditions, reflecting the genetic improvement of the materials under stress conditions (Tosquy-Valle *et al*., 2020); additionally, these values were lower than those achieved in seven native varieties under Mediterranean conditions (29.25 to 39.69 g) (Kargiotidou *et al*., 2019). However, WHSE of up to 98.39 g has been reported (Sinkoviè *et al*., 2019); these differences are attributed to both the variety and climatic conditions (Sánchez-Reynoso *et al*., 2020). The Noche buena variety was not considered due to germination problems and lengthening of the cycle. Meanwhile, the similar yield between the native varieties, the grains and the improved variety show climatic plasticity, highlighting the Negro milpa and Tlalchete varieties with yields equal to Negro and Güero Amatlán, the latter as varieties adapted to the experimental site.

CONCLUSION

The variation reported through the qualitative and quantitative characters of the morpho–agronomic variables of the bean seeds is the result of adaptation to the variation in climatic and edaphic factors where they were cultivated for several generations. The regional diversity of bean varieties shows a viable germplasm to be used in genetic diversity management and conservation programs; in addition, it is a reference collection, crucial for food security and agricultural sustainability.

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Conflict of interest

All authors declared that there is no conflict of interest.

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