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Lucia Emperatriz Escalante Ortiz (✉ leescalanteo@unc.edu.pe)
Instituto Nacional de Innovación Agraria
Angel Esteban Santa Cruz Padilla
Instituto Nacional de Innovación Agraria
Araceli Eugenio Leiva
Instituto Nacional de Innovación Agraria
Jorge Luis Vasquez Orrillo
Instituto Nacional de Innovación Agraria
Silvia Yanina Rodriguez Lopez
Instituto Nacional de Innovación Agraria
Susan Haydee Soriano Morales
Juan Fransisco Seminario Cunya

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Lucia E. Escalante Ortiz [1]*
leescalanteo@unc.edu.pe
ORCID: 0000-0002-9559-9604
Angel E. Santa Cruz Padilla [1]
asantacruz@inia.gob.pe
Araceli Eugenio Leiva [1]
araceli22eugenio@gmail.com
Jorge L. Vasquez Orrillo[1]
jorgelvo1605@gmail.com
Silvia Y. Rodriguez Lopez [1]
srodriguezl13@unc.edu.pe
[1]Instituto Nacional de Innovacion Agraria
Wiracocha street, Baños del Inca, Cajamarca, Peru
*Corresponding autor

Susan H. Soriano Morales[2]
[2]State University of Campinas
susan.soriano@gmail.com
Zeferino Vaz University City - Barão Geraldo, Campinas - SP, 13083-970, Brazil

Juan F. Seminario Cunya[3]
[3]Universidad Nacional de Cajamarca
jseminario@unc.edu.pe
1050 Atahualpa AV. Cajamarca, Peru

Abstract

Amaranth is a promising crop for the Cajamarca region and Peru. The National Institute of Agrarian Innovation (INIA) from Peru preserves a national collection of 552 amaranth accessions; however, there needs to be a detailed study of the morphology of these materials. In this research, 65 accessions were morphologically characterized based on their place of origin, using 21 descriptors standardized by INIA-Peru. The clustering of accessions and principal component analysis showed the presence of 38 groups and a duplication rate of 41.5% of accessions at a taxonomic distance of 0.62. In addition, 18 morphological characters that significantly contributed to morphological variability were identified and explained by the first six principal components. Due to the scarcity of studies on amaranth, it is recommended to conduct more characterization and molecular studies to obtain better approximations of the genetic diversity of the amaranth germplasm to be used on amaranth plant breeding programs.

Keywords: Kiwicha; Principal components . Phenotypic diversity . Clustering . Peruvian agrobiodiversity

Introduction

Peru is known for being the birthplace of ancient civilizations that domesticated crops of global importance, such as potatoes, corn, quinoa, kiwicha, and cañihua, before the Incas. According to (Adhikary and Pratt 2015; Costea et al. 2006; Sauer 1967), kiwicha or amaranth (*Amaranthus caudatus* L.), an Andean grain adapted to low temperatures, originated in the Andes, and was cultivated by pre-Inca and Inca civilizations. Amaranth is a promising crop due to its high nutritional value, mainly due to its content of protein, essential amino acids, fiber, and bioavailable iron (Joshi and Chandra 2020; Tucker 1986). The *Amaranthus* genus comprises between 50 and 75 species distributed worldwide, of which 60 are native to the American continent, and ten are distributed in Asia, Africa, Australia, and Europe (Alegbejo 2014; Sauer 1967). Amaranths had nutritional, historical, and cultural significance in America, especially for the Incas and Aztecs, until the arrival of the Spanish (Veneros and Chico 2017). The Andes of South America are a center of origin, domestication, and dispersion of pseudocereals with high nutritional content, such as amaranth, quinoa, and cañihua, according to Hawkes (1999). The species *A. caudatus*, *A. cruentus*, and *A. hypochondriacus*, cultivated for grain, were domesticated in the American continent, and grown in Mexico, Central America, and the Andes for thousands of years (Sauer 1967).

In Peru, research on amaranth is scarce, and the existing reports must be more formal and precise. Therefore, the morphological variability of amaranth in the country has yet to be discovered, despite its diversity and potential for improvement. However, the National Institute of Agrarian Innovation (INIA) has made significant progress in amaranth research over the past 25 years, releasing three improved varieties and having three promising cultivars under development (INIA 2006a; INIA 2006b; INIA 2012; Perez 2010). Furthermore, according to Alvarez et al. (2013), the National University San Antonio Abad of Cusco has 790 amaranth accessions, while the Baños del Inca Agrarian Experimental Station of the INIA maintains the national amaranth gene bank with 552 accessions, including 65 collected in the Cajamarca region between 1985 and 1986.

Genetic resource characterization explains hereditary traits that range from morphological to molecular markers (Hassen et al. 2006), involving the recording and compiling of data on essential traits that distinguish one species from another and accessions or varieties within species to allow for easy and rapid discrimination between phenotypes (Bioversity International 2007). Plant characterization is vital to reveal desirable characteristics for farmers and plant breeders (Bucheyeki et al. 2010; Laurentin, 2009) to obtain high-quality and high-yielding varieties (Laurentin 2009). This study aimed to determine the morphological variability of 65 amaranth accessions from the Cajamarca region.

Materials and methods

The study was conducted during the 2005-2006 crop season in the Cochamarca experimental annex of the National Institute of Agrarian Innovation. Sixty-five accessions from the Cajamarca region (Table 1) were used. Twenty-one morphological descriptors (Table 2) belonging to INIA were applied to characterize the accessions. The plants were systematically sown, with one accession per row and an average of 25 plants per row. The morphological characteristics of each plant were observed, discarding those that did not correspond to the predominant plant type.

The data obtained from the morphological characterization was compiled into a basic data matrix (BDM) in Excel version 2019 for further analysis. The BDM was organized under the arrangement a x b, where the "a" column represent the evaluated morphological descriptors and the "b" rows represent the evaluated amaranth accessions. Each cell in the Excel matrix represented the value or state of the descriptor in the corresponding amaranth accessions (Crisci and López 1983; Hidalgo 2003).

With the BDM, multivariate statistical analysis was performed using the NTSYSpc program (Numeral Taxonomy System, version 2.20N), allowing for cluster and principal component analyses (PCA). The cluster analysis determined the morphological closeness between accessions through a phenogram that allowed for the identification of groups of morphologically different and similar (duplicate) accessions. The relationship between descriptors (associated and non-associated), the similarity between accessions, and the identification of discriminatory descriptors were determined with PCA (Crisci and Lopez, 1983; Hidalgo 2003).

Results

Cluster analysis and principal component analysis:

Cluster analysis

In the evaluated amaranth collection, duplicates were detected, and groups of accessions were identified through cluster analysis. Figure 1 shows that if a similarity coefficient of 1.56 is considered, five groups are formed, one of which is formed by 59 accessions, one of three accessions, and three more groups included one accession each. However, considering an intermediate taxonomic distance (coefficient 0.62, as shown in Figure 1), the collection is divided into 38 groups, indicating a 41.5% duplication. Group III has nine accessions, while group VIII is the second largest, with six accessions. Additionally, there are three groups (II, IV, and V), each consisting of four accessions. Group VI consisted of three accessions, while three groups (I, VII, and IX) included two accessions each, and 29 groups comprised only one accession each. If the maximum level of similarity is considered (coefficient 0.00), the collection is classified into 61 groups, with four groups comprising two accessions each and 57 groups with one accession each.

Principal component analysis

Principal component analysis (PCA) allowed for determining the contribution of each component to the variation of morphological traits in the evaluated amaranth collection. Of the six selected components based on their correlation coefficient value, 70.8% of the total variation in the collection was explained. The first component had the highest contribution (25.9%) to the variation of traits. The first component included: four leaf traits (leaf color [LC], leaf pubescence [LP], petiole color [PC], and leaf edge [LE]), two inflorescence traits (inflorescence color before maturity [ICBM] and inflorescence color at maturity [ICM]), and two stem traits (stem color [SC] and stem pubescence [SP]).

Group six (70.8% of variation) only included two components, one for stem and one for root. Additionally, the PCA demonstrated that a tremendous variation was explained by 20 morphological traits with correlation coefficients ≥ of 0.50, corresponding to six leaf traits, six stem traits, five inflorescence traits, two-grain traits, and one root trait (Table 4).

In Figure 2, it is illustrated that the correlation between the first two principal components is of utmost importance, accounting for 40.3% of the total variation. Additionally, this correlation confirms the clustering of 40 amaranth accessions as a differentiated group from the other accessions. This group is characterized by its green, pubescent stems, dark green elliptical leaves with wavy or entire edges, and well-differentiated terminal inflorescences that are purple-red and greyish-purple in color before physiological maturity. A second group included four accessions (PER002330 - Coyo Amoshulca, PER002336 - Coyo Otuzco 5, PER002371 - Coyo Blanco, and PER002428 - Coyo), which had yellow-green and glabrous stems, yellow-green elliptical leaves with entire edges, and well-differentiated terminal inflorescences that are also yellowish- green in color before physiological maturity. Finally, the third group included only three accessions (PER002385 - Coyo, PER002589 - Black Coyo, and PER002499 - Cancha Quinua), known for their green pigmented with red pubescent stems. Furthermore, these three accessions exhibit a terminal inflorescence that ranges from red to greyish-purple before reaching physiological maturity. These results indicate a clear differentiation between amaranth accession groups based on the evaluated morphological characteristics.

Discussion

The accession grouping based on morphological characteristics revealed variability in the germplasm. Among the 38 groups formed at the intermediate taxonomic distance (coefficient 0.62), group III, consisting of nine accessions, exhibits similarities in 18 out of 21 morphological traits. However, significant differences were observed in three key characteristics, named inflorescence density (ID), main inflorescence posture (IP), and grain color (GC). Six accessions' inflorescence density (ID) was compact, while the inflorescences of accessions PER2333, PER2553, and PER2339 exhibited an intermediate density. Five accessions exhibited semi-erect inflorescences, while the remaining four had erect inflorescences. Furthermore, grain color varied from white to greyish-yellow and greyish-orange.

The analysis suggests that although the nine accessions were classified under the same group III, some genetic variations in their morphological traits still exist. The observed differences in grain color (GC) among the individuals in Group III make them potentially valuable materials for developing varieties that can be utilized in the agro-industry. Moreover, accessions belonging to Group VIII exhibit essential traits, such as branching, well-differentiated, and compact terminal inflorescences, that are typically more productive than unbranched accessions with lax inflorescences. Similarly, accessions in other groups possess significant morphological characteristics that can aid in developing new varieties. The most significant morphological variability was observed among groups with only one accession, and such groups can be preserved in seed banks for future studies.

The first two components for the morphological data groups explained over 70% of the variance. As per Crisci and Lopez's (1983) explanation, this accounts for the observed individual variability. Key morphological traits such as leaf color (LC), leaf pubescence (LP), inflorescence color before maturity (ICBM), inflorescence color at maturity (ICM), petiole color (PC), stem color (SC), leaf edge (LE), stem pubescence (SP), inflorescence type (IT), and leaf shape (LS) exhibited a substantial contribution to both the PC1 and PC2 axes. Consequently, it is possible to genetically improve amaranth by selecting morphological characters of agronomic importance. In Cajamarca, new productive varieties of amaranth can be identified by selecting accessions with higher CP1 and CP2 values in the morphological groups. Accessions with low CP1 and CP2 values can also be used in plant breeding to obtain ornamental varieties, thanks to the purple-red color of their inflorescences and abundance of branches.

The study conducted in the Cajamarca region suggests that the grouping of amaranths is only sometimes related to their place of origin, as farmers in the region have exchanged seeds in recent years. However, it is worth noting that four accessions in group II were collected from Jesús and Baños del Inca districts, both in the province of Cajamarca (Figure 3). This research offers significant insights into the genetic diversity of amaranths in Cajamarca, Peru, which is essential for advancing plant breeding programs. The findings underscore the potential of utilizing individuals with grain color variations to develop novel varieties in the agro-industry. Furthermore, it highlights the significance of categorizing accessions into similar genetic and morphological groups for germplasm conservation initiatives and parent selection.

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Competing Interests

All the authors declare that they have no conflicts of interest.

Authors contributions

Lucia Emperatriz Escalante Ortiz, Jorge Luis Vasquez Orrillo, Angel Esteban Santa Cruz Padilla, and Juan Francisco Seminario Cunya contributed to the study conception and design. Araceli Eugenio Leiva, Lucia Emperatriz Escalante Ortiz, Jorge Luis Vasquez Orrillo, Silvia Yanina Rodriguez Lopez, and Susan Haydee Soriano Morales performed material preparation, data organization, and analysis. The first draft of the manuscript was written by Lucia Emperatriz Escalante Ortiz and revised by all authors. All authors read and approved the final manuscript.

Competing Interests

All the authors declare that they have no conflicts of interest.

Data availability

The datasets generated during the current study are available from the corresponding author upon reasonable request.

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Table 1 Passport data of 65 amaranth accessions from the Cajamarca Region, Peru.

Nº	Accesion code	Local name	Province of collection	District of collection	Village of collection	Latitude	Longitude	Altitude (m)
1	PER2330	Coyo Amoshulca	Cajamarca	Cajamarca	Cajamarca	-7.15676	-78.51907	2735
2	PER2331	Coyo Amoshulca	Cajamarca	Cajamarca	Cajamarca	-7.15676	-78.51907	2735
3	PER2332	Coyo Otuzco	Cajamarca	Cajamarca	Alto Otuzco	-7.13609	-78.45517	2762
4	PER2333	Coyo Huambocancha	Cajamarca	Cajamarca	Huambocancha	-7.10337	-78.54605	2863
5	PER2334	Coyo Colorquegua	Cajamarca	Cajamarca	Cajamarca	-7.15676	-78.51907	2735
6	PER2335	Coyo Otuzco	Cajamarca	Cajamarca	Alto Otuzco	-7.13609	-78.45517	2762
7	PER2336	Coyo Otuzco	Cajamarca	Cajamarca	Alto Otuzco	-7.13609	-78.45517	2762
8	PER2337	Coyo Cajamarca	Cajamarca	Cajamarca	Cajamarca	-7.15676	-78.51907	2735
9	PER2338	Coyo Namora	Cajamarca	Cajamarca	Namora	-7.2015	-78.32607	2747
10	PER2339	Coyo San Marcos	San Marcos	San Marcos	San Marcos	-7.33551	-78.17028	2261
11	PER2340	Coyo Celendin	Celendin	Celendin	Celendin	-6.86749	-78.14617	2634
12	PER2341	Coyo Mollepata	Cajamarca	Cajamarca	Mayopata	-7.13789	-78.52649	2755
13	PER2342	Coyo San Luis	Cajamarca	Cajamarca	San Luis	-7.15701	-78.51748	2726
14	PER2343	Coyo San Miguel	San Miguel	San Miguel	San Miguel	-6.99932	-78.8511	2611
15	PER2345	Coyo Negro	Celendin	Celendin	Celendin	-6.86749	-78.14617	2634
16	PER2346	Coyo	Cajamarca	Cajamarca	Huambocancha	-7.11517	-78.53218	2826
17	PER2347	Coyo	Cajamarca	Cajamarca	Huambocancha	-7.11517	-78.53218	2826
18	PER2348	Coyo	Cajamarca	Cajamarca	Huambocancha	-7.11517	-78.53218	2826
19	PER2367	Coyo	Cajamarca	Cajamarca	Cerrillo	-7.12030	-78.49129	2740
20	PER2368	Coyo	Cajamarca	Cajamarca	Quinrayquero	-7.11035	-78.50126	2901
21	PER2369	Coyo	Cajabamba	Cajabamba	Chanshapamba	-7.66748	-78.05181	2889
22	PER2371	Coyo Blanco	Cajamarca	Cajamarca	Jesus	-7.24933	-78.37886	2561
23	PER2373	Quinua Cancha	Hualgayoc	Hualgayoc	Bambamarca	-6.67810	-78.52152	2537
24	PER2374	Coyo	Hualgayoc	Hualgayoc	Chulipampa	-6.75416	-78.55838	3045
25	PER2375	Coyo Blanco	Cajamarca	Cajamarca	Jesus	-7.24933	-78.37886	2561
26	PER2376	Coyo Rojo Cajamarquino	Cajamarca	Cajamarca	Cajamarca	-7.15676	-78.51907	2735
27	PER2377	Coyo Rosado	Cajamarca	Cajamarca	Jesus	-7.24933	-78.37886	2561
28	PER2378	Coyo Blanco	Cajamarca	Cajamarca	Jesus	-7.24933	-78.37886	2561
29	PER2380	Coyo	Cajamarca	Cajamarca	Jesus	-7.24933	-78.37886	2561
30	PER2385	Coyo	Celendin	Celendín	Chogopampa	-6.91741	-78.26900	2792
31	PER2386	Coyo	Cajabamba	Cajabamba	Callash	-7.63970	-78.06299	2756
32	PER2387	Coyo Rosado	Celendin	Celendín	Sorochuco	-6.91095	-78.25475	2659
33	PER2428	Coyo	Cajamarca	Cajamarca	Jesus	-7.24933	-78.37886	2561
34	PER2429	Kiwicha	Hualgayoc	Hualgayoc	Bambamarca	-6.67810	-78.52152	2537
35	PER2430	Kiwicha	Hualgayoc	Hualgayoc	Bambamarca	-6.67810	-78.52152	2537
36	PER2431	Kiwicha	Santa Cruz	Santa Cruz	Santa Cruz	-6.62709	-78.94482	2028
37	PER2445	Coyo	Santa Cruz	Santa Cruz	Santa Cruz	-6.62709	-78.94482	2028
38	PER2447	Kiwicha	San Miguel	San Miguel	Sumiden	-7.01554	-78.85670	2444
39	PER2448	Kiwicha Negra	San Miguel	San Miguel	Lanche Pampa	-7.01855	-78.90341	2848
40	PER2451	Kiwicha Cancha	San Miguel	San Miguel	Tongod Bajo	-6.76239	-78.82111	2658

41	PER2470	Quinua Cancha	Hualgayoc	Hualgayoc	Chala Saucebamba	-6.67292	-78.50412	2638
42	PER2471	Kiwicha	Santa cruz	Santa cruz	Santa Cruz	-6.62709	-78.94482	2028
43	PER2498	Cancha Quinua	San Miguel	San Miguel	Lanche Pampa	-7.01855	-78.90341	2848
44	PER2499	Cancha Quinua	San Miguel	San Miguel	Chuad	-7.01145	-78.88943	2802
45	PER2500	Coyo	Celendin	Celendin	Catalina	-6.66792	-78.24873	3136
46	PER2501	Kiwicha	Celendin	Celendin	Santa Rosa	-6.86341	-78.12678	2829
47	PER2502	Kiwicha	Hualgayoc	Hualgayoc	San Antonio	-6.64690	-78.52957	2756
48	PER2503	Kiwicha Morada	Celendin	Celendin	Surupata	-6.90138	-78.25670	3062
49	PER002506	Kiwicha	Cutervo	Cutervo	Yatun	-6.36739	-78.75638	2164
50	PER2508	Kiwicha	Cajamarca	Cajamarca	Sulluscocha	-7.19530	-78.39076	2865
51	PER2553	Coyo	Celendin	Celendin	Celendin	-6.86749	-78.14617	2634
52	PER2554	Coyo	Celendin	Celendin	Celendin	-6.86749	-78.14617	2634
53	PER2559	Coyo	Cajamarca	Cajamarca	Chetilla	-7.14684	-78.67400	2785
54	PER2577	Kiwicha	Hualgayoc	Hualgayoc	Huangamarca	-6.64640	-78.46612	2688
55	PER2578	Coyo Negro	Celendin	Celendin	Quillimbash	-6.91924	-78.18125	2880
56	PER2579	Coyo Rosado	Celendin	Celendin	Quillimbash	-6.91924	-78.18125	2880
57	PER2580	Coyo Rosado	Celendin	Celendin	La Collona	-6.87884	-78.21827	2905
58	PER2581	Kiwicha	Cajamarca	Cajamarca	La Gloria	-7.16212	-78.46303	2667
59	PER2587	Coyo Negro	Celendin	Celendin	Surupata	-6.90138	-78.25670	3062
60	PER2588	Coyo Blanco	Celendin	Celendin	Surupata	-6.90138	-78.25670	3062
61	PER2589	Coyo Negro	Cajabamba	Cajabamba	Pampa Grande	-7.60974	-78.06203	2641
62	PER2590	Coyo o Atago Negro	Cajabamba	Cajabamba	Pampa Grande	-7.60974	-78.06203	2641
63	PER2792	Achita Coyo	San Marcos	San Marcos	Cochamarca	-7.28105	-78.21933	2842
64	PER2793	Achita Nepal	San Marcos	San Marcos	Cochamrca	-7.28105	-78.21933	2842
65	PER2828	Achita	Cajamarca	Cajamarca	Namora	-7.20150	-78.32607	2747

Table 2 List of morphological descriptors used to characterize the 65 accessions of amaranths from Cajamarca Region.

Character abbreviation	Character	States of the character	Plant phenological stage during evaluation	Nº of plants evaluated per accession
PH	Plant habit	1 erect; 2 semi-erect; 3 decumbent	Flowering	5
RB	Root branching	1 low branching; 2 high branching	Flowering	5
SP	Stem pubescence	0 absent; 1 present	Flowering	5
SC	Stem color	1 yellowish- green; 2 green; 3 green pigmented with red at the base; 4 green with purple-red stripes; 5 grayish-purple; 6 grayish-red with green stripes; 7 purple-red; 8 orange-yellow	Flowering	5
SS	Stem shape	1 cylindrical without longitudinal stripes; 2 cylindrical with superficial longitudinal stripes; 3 cylindrical with deep longitudinal stripes	Flowering	5
PBS	Presence of branching on the main stem	0 without branches; 1 few branches and all near the base of the stem; 2 many branches and all near the base of the stem; 3 all branches along the stem	Flowering	5
LS	Leaf shape	1 lanceolate; 2 elliptical; 3 acuminate; 4 ovate; 5 rhomboid-ovate; 6 rhombic; 7 oval	Flowering	5
LC	Leaf color	1 yellowish- green; 2 green; scale 3 dark green; 4 green pigmented with red or black; 5 purple; scale 6 grayish-purple; 7 green with orange-grayish or purple bands; 8 others	Flowering	5
LP	Leaf pubescence	0 absent; 1 present	Flowering	5
LE	Leaf edge	1 entire; 2 dentate; 3 undulate	Flowering	5
PC	Petiole color	1 light green; 2 green with purple pigmentation; 3 entirely purple- red; 4 others	Flowering	5
VPUL	Vein prominence on the underside of the leaf	1 not prominent; 2 prominent	Flowering	5
IT	Inflorescence type	1 terminal and well differentiated from the rest of the plant; 2 not differentiated	Beginning of physiological maturity	5
IS	Inflorescence shape	1 amaranthiform; 2 clustered	During physiological maturity	5
ID	Inflorescence density	1 lax; 2 intermediate; 3 compact or dense	During physiological maturity	5
IP	Inflorescence posture	1 erect; 2 semi-erect; 3 decumbent	During physiological maturity	5
ICBM	Inflorescence color before maturity	1 yellowish- green; 2 yellow; 3 greyish-orange; 4 red; 5 purple- red; 6 purple; 7 grayish- purple; 8 yellowish- green with purple bands; 9 others	Flowering	5
ICM	Inflorescence color at maturity	1 yellowish- green; 2 yellow; 3 grayish-orange; 4 red; 5 purple- red; 6 purple; 7 grayish- purple; 8 yellowish- green with purple bands; 9 others	During physiological maturity	5
GC	Grain color	1 orange- white; 2 grayish-orange; 3 grayish-yellow; 4 grayish-red; 5 brown	After harvest	5
GT	Grain type	1 translucent or hyaline; 2 intermediate; 3 opaque	After harvest	5
GS	Grain shape	1 round; 2 ellipsoidal to ovoid	After harvest	5

The color of the stem, leaf, inflorescence, and seed was recorded using the color chart of the Royal Horticultural Society.

Table 3 Main components, eigenvalues and proportion of total variance explained by the first six principal components of 65 amaranth accessions from the Cajamarca region, characterized by 21 morphological descriptors.

Main componentes	**Eigenvalues**	**Proportion of total variance explained**	
		Absolute (%)	**Cumulative (%)**
1	5.442	25.916	25.916
2	3.038	14.466	40.381
3	2.096	9.981	50.362
4	1.753	8.349	58.711
5	1.536	7.313	66.024
6	1.011	4.814	70.838

Table 4 Six principal components, proportion of total variance, traits, and correlation coefficients in the characterization of 65 amaranth accessions collected from the Cajamarca region

Main components	**Percentage of total variance**	**Characters**	**Correlation coefficient**
CP1	25.916	Leaf color (LC)	0.924
		Leaf pubescence (LP)	0.839
		Inflorescence color before physiological maturity (ICBM)	0.831
		Inflorescence color at maturity (ICM)	0.755
		Petiole color (PC)	0.748
		Stem color (SC)	0.699
		Leaf edge (LE)	0.649
		Stem pubescence (SP)	0.518
CP2	40.381	Stem color (SC)	0.509
		Inflorescence type (IT)	0.781
		Leaf shape (LS)	0.689
CP3	50.362	Vein prominence on the underside of the leaf (VPUL)	0.683
		Inflorescence shape (IS)	0.615
CP4	58.711	Grain Type (GT)	0.714
		Stem shape (SS)	0.613
		Grain shape (GS)	0.587
CP5	66.024	Inflorescence posture (IP)	0.576
		Presence of branching on the main stem (PBS)	0.561
CP6	70.838	Root branching (RB)	0.665
		Stem pubescence (SP)	0.5051

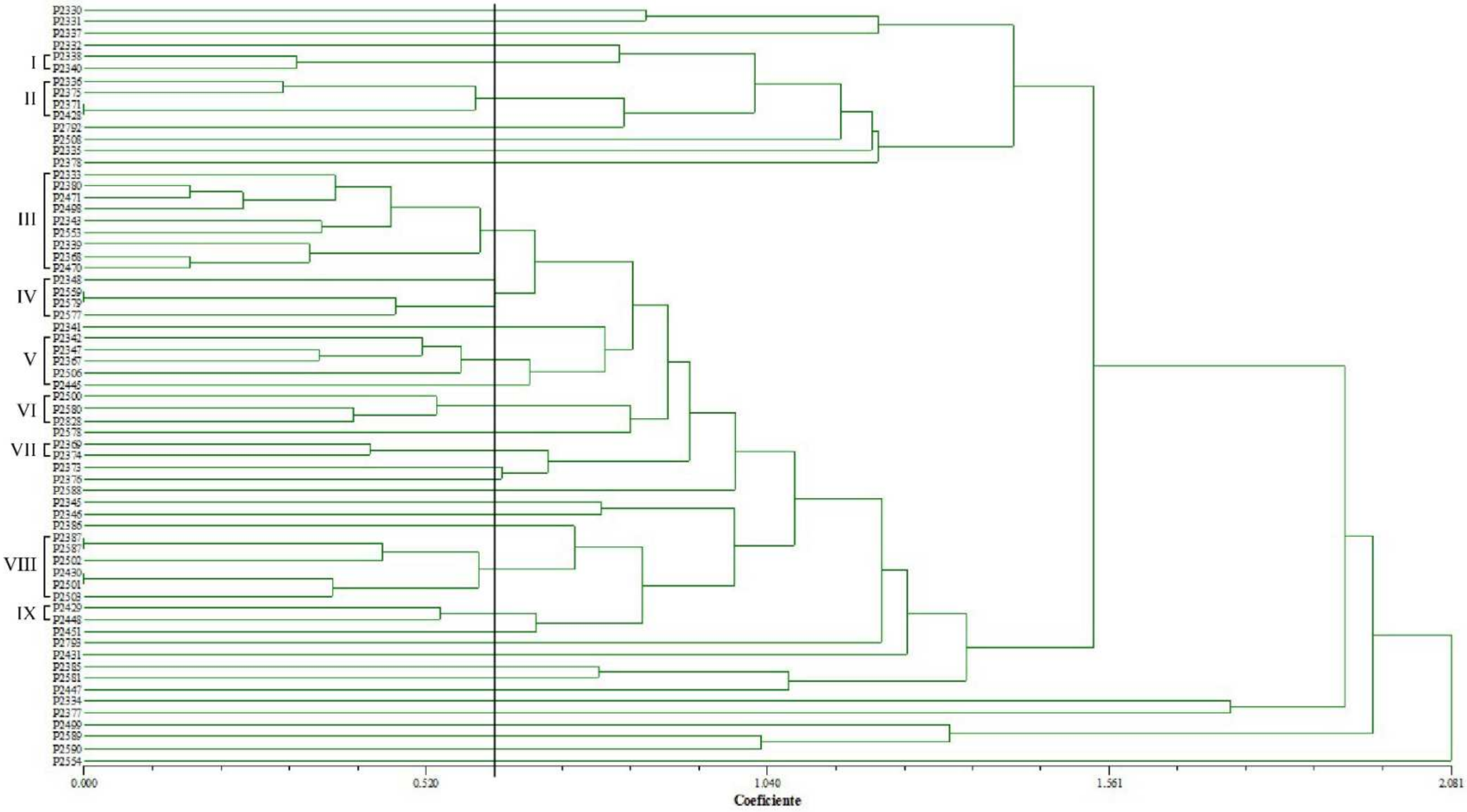

Fig. 1 Fenogram based on 21 morphological descriptors for the 65 amaranth accessions from the Cajamarca Region, Peru

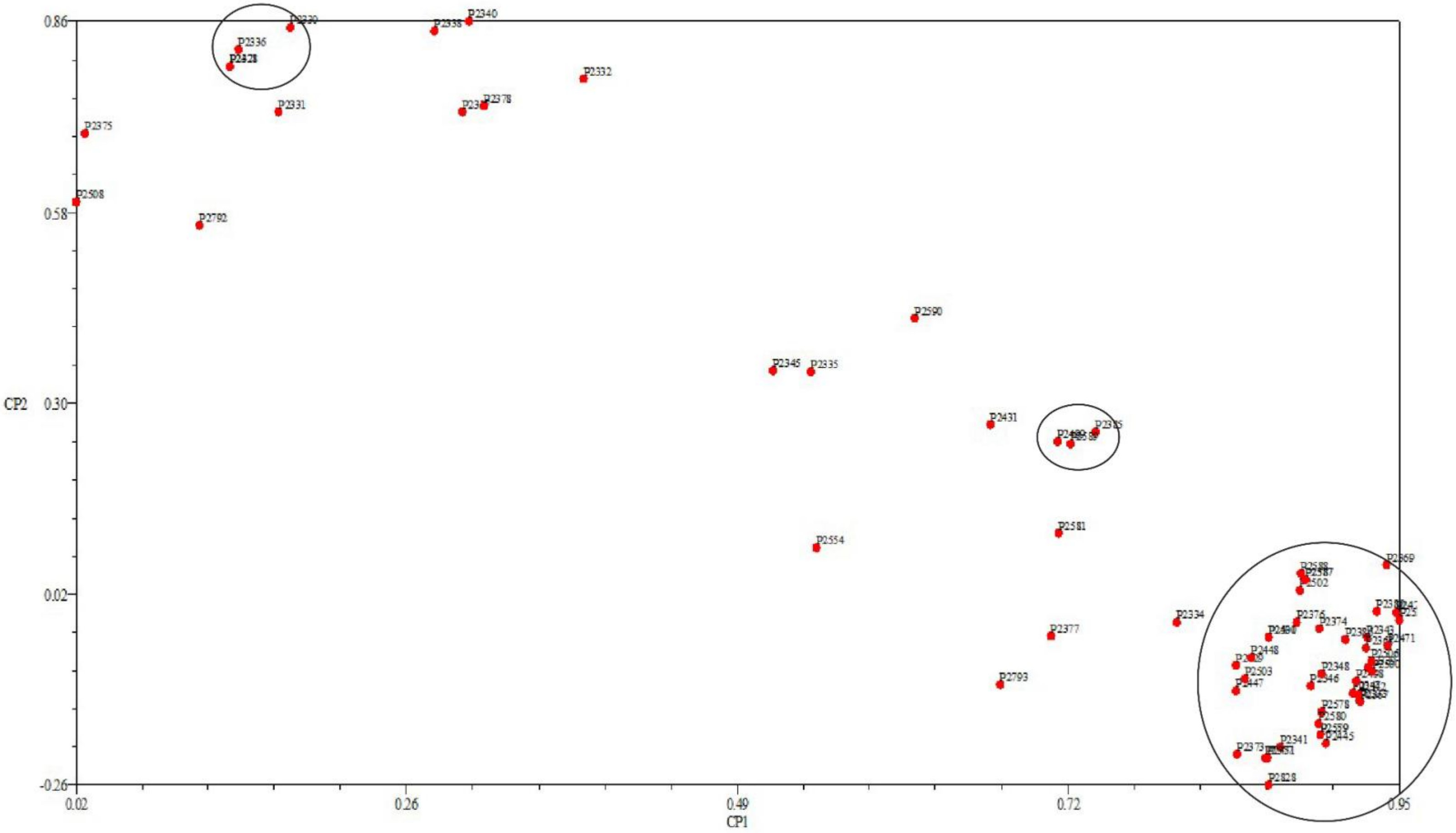

Fig. 2 Dispersion of 65 amaranth accessions from the Cajamarca Region in the first and second main components with 21 morphological descriptors

Illustrator artwork program was used to edit figures 1 and 2.