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Morphological variability of 65 amaranth accessions from the Cajamarca Region, Peru

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Research Article

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29 Abstract

30 Amaranth is a promising crop for the Cajamarca region and Peru. The National Institute of Agrarian 31 Innovation (INIA) from Peru preserves a national collection of 552 amaranth accessions; however, there 32 needs to be a detailed study of the morphology of these materials. In this research, 65 accessions were 33 morphologically characterized based on their place of origin, using 21 descriptors standardized by INIA-Peru. 34 The clustering of accessions and principal component analysis showed the presence of 38 groups and a 35 duplication rate of 41.5% of accessions at a taxonomic distance of 0.62. In addition, 18 morphological 36 characters that significantly contributed to morphological variability were identified and explained by the first 37 six principal components. Due to the scarcity of studies on amaranth, it is recommended to conduct more 38 characterization and molecular studies to obtain better approximations of the genetic diversity of the amaranth 39 germplasm to be used on amaranth plant breeding programs. 40

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

42 Introduction

43 Peru is known for being the birthplace of ancient civilizations that domesticated crops of global 44 importance, such as potatoes, corn, quinoa, kiwicha, and cañihua, before the Incas. According to (Adhikary 45 and Pratt 2015; Costea et al. 2006; Sauer 1967), kiwicha or amaranth (Amaranthus caudatus L.), an Andean 46 grain adapted to low temperatures, originated in the Andes, and was cultivated by pre-Inca and Inca 47 civilizations. Amaranth is a promising crop due to its high nutritional value, mainly due to its content of 48 protein, essential amino acids, fiber, and bioavailable iron (Joshi and Chandra 2020; Tucker 1986). 49 The Amaranthus genus comprises between 50 and 75 species distributed worldwide, of which 60 are native to 50 the American continent, and ten are distributed in Asia, Africa, Australia, and Europe (Alegbejo 2014; Sauer 51 1967). Amaranths had nutritional, historical, and cultural significance in America, especially for the Incas and 52 Aztecs, until the arrival of the Spanish (Veneros and Chico 2017). The Andes of South America are a center 53 of origin, domestication, and dispersion of pseudocereals with high nutritional content, such as amaranth, 54 quinoa, and cañihua, according to Hawkes (1999). The species A. caudatus, A. cruentus, and A. 55 hypochondriacus, cultivated for grain, were domesticated in the American continent, and grown in Mexico, 56 Central America, and the Andes for thousands of years (Sauer 1967). 57 In Peru, research on amaranth is scarce, and the existing reports must be more formal and precise. 58 Therefore, the morphological variability of amaranth in the country has yet to be discovered, despite its 59 diversity and potential for improvement. However, the National Institute of Agrarian Innovation (INIA) has 60 made significant progress in amaranth research over the past 25 years, releasing three improved varieties and 61 having three promising cultivars under development (INIA 2006a; INIA 2006b; INIA 2012; Perez 2010). 62 Furthermore, according to Alvarez et al. (2013), the National University San Antonio Abad of Cusco has 790 63 amaranth accessions, while the Baños del Inca Agrarian Experimental Station of the INIA maintains the 64 national amaranth gene bank with 552 accessions, including 65 collected in the Cajamarca region between 65 1985 and 1986. 66 Genetic resource characterization explains hereditary traits that range from morphological to 67 molecular markers (Hassen et al. 2006), involving the recording and compiling of data on essential traits that 68 distinguish one species from another and accessions or varieties within species to allow for easy and rapid 69 discrimination between phenotypes (Bioversity International 2007). Plant characterization is vital to reveal

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- 70 desirable characteristics for farmers and plant breeders (Bucheyeki et al. 2010; Laurentin, 2009) to obtain
- 71 high-quality and high-yielding varieties (Laurentin 2009). This study aimed to determine the morphological
- variability of 65 amaranth accessions from the Cajamarca region.
- 73

74 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

80 correspond to the predominant plant type.

81 The data obtained from the morphological characterization was compiled into a basic data matrix

82 (BDM) in Excel version 2019 for further analysis. The BDM was organized under the arrangement a x b,

83 where the "a" column represent the evaluated morphological descriptors and the "b" rows represent the

84 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).

86 With the BDM, multivariate statistical analysis was performed using the NTSYSpc program

87 (Numeral Taxonomy System, version 2.20N), allowing for cluster and principal component analyses (PCA).

88 The cluster analysis determined the morphological closeness between accessions through a phenogram that

89 allowed for the identification of groups of morphologically different and similar (duplicate) accessions. The

90 relationship between descriptors (associated and non-associated), the similarity between accessions, and the

91 identification of discriminatory descriptors were determined with PCA (Crisci and Lopez, 1983; Hidalgo

92 2003).

93

94 Results

95 Cluster analysis and principal component analysis:

96 Cluster analysis

97 In the evaluated amaranth collection, duplicates were detected, and groups of accessions were 98 identified through cluster analysis. Figure 1 shows that if a similarity coefficient of 1.56 is considered, five 99 groups are formed, one of which is formed by 59 accessions, one of three accessions, and three more groups 100 included one accession each. However, considering an intermediate taxonomic distance (coefficient 0.62, as 101 shown in Figure 1), the collection is divided into 38 groups, indicating a 41.5% duplication. Group III has 102 nine accessions, while group VIII is the second largest, with six accessions. Additionally, there are three 103 groups (II, IV, and V), each consisting of four accessions. Group VI consisted of three accessions, while three 104 groups (I, VII, and IX) included two accessions each, and 29 groups comprised only one accession each. If the 105 maximum level of similarity is considered (coefficient 0.00), the collection is classified into 61 groups, with 106 four groups comprising two accessions each and 57 groups with one accession each. 107 108 **Principal component analysis** 109 Principal component analysis (PCA) allowed for determining the contribution of each component to 110 the variation of morphological traits in the evaluated amaranth collection. Of the six selected components 111 based on their correlation coefficient value, 70.8% of the total variation in the collection was explained. The 112 first component had the highest contribution (25.9%) to the variation of traits. The first component included: 113 four leaf traits (leaf color [LC], leaf pubescence [LP], petiole color [PC], and leaf edge [LE]), two 114 inflorescence traits (inflorescence color before maturity [ICBM] and inflorescence color at maturity [ICM]), 115 and two stem traits (stem color [SC] and stem pubescence [SP]). 116 Group six (70.8% of variation) only included two components, one for stem and one for root. Additionally, 117 the PCA demonstrated that a tremendous variation was explained by 20 morphological traits with correlation 118 coefficients \geq of 0.50, corresponding to six leaf traits, six stem traits, five inflorescence traits, two-grain traits, 119 and one root trait (Table 4). 120 In Figure 2, it is illustrated that the correlation between the first two principal components is of 121 utmost importance, accounting for 40.3% of the total variation. Additionally, this correlation confirms the 122 clustering of 40 amaranth accessions as a differentiated group from the other accessions. This group is 123 characterized by its green, pubescent stems, dark green elliptical leaves with wavy or entire edges, and well-124 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

126 Otuzco 5, PER002371 - Coyo Blanco, and PER002428 - Coyo), which had yellow-green and glabrous stems,

127 yellow-green elliptical leaves with entire edges, and well-differentiated terminal inflorescences that are also

128 yellowish- green in color before physiological maturity. Finally, the third group included only three

129 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

131 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 morphologicalcharacteristics.

134

135 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

142 accessions exhibited semi-erect inflorescences, while the remaining four had erect inflorescences.

143 Furthermore, grain color varied from white to greyish-yellow and greyish-orange.

144 The analysis suggests that although the nine accessions were classified under the same group III, 145 some genetic variations in their morphological traits still exist. The observed differences in grain color (GC) 146 among the individuals in Group III make them potentially valuable materials for developing varieties that can 147 be utilized in the agro-industry. Moreover, accessions belonging to Group VIII exhibit essential traits, such as 148 branching, well-differentiated, and compact terminal inflorescences, that are typically more productive than 149 unbranched accessions with lax inflorescences. Similarly, accessions in other groups possess significant 150 morphological characteristics that can aid in developing new varieties. The most significant morphological 151 variability was observed among groups with only one accession, and such groups can be preserved in seed 152 banks for future studies.

153 The first two components for the morphological data groups explained over 70% of the variance. As 154 per Crisci and Lopez's (1983) explanation, this accounts for the observed individual variability. Key 155 morphological traits such as leaf color (LC), leaf pubescence (LP), inflorescence color before maturity 156 (ICBM), inflorescence color at maturity (ICM), petiole color (PC), stem color (SC), leaf edge (LE), stem 157 pubescence (SP), inflorescence type (IT), and leaf shape (LS) exhibited a substantial contribution to both the 158 PC1 and PC2 axes. Consequently, it is possible to genetically improve amaranth by selecting morphological 159 characters of agronomic importance. In Cajamarca, new productive varieties of amaranth can be identified by 160 selecting accessions with higher CP1 and CP2 values in the morphological groups. Accessions with low CP1 161 and CP2 values can also be used in plant breeding to obtain ornamental varieties, thanks to the purple-red 162 color of their inflorescences and abundance of branches. 163 The study conducted in the Cajamarca region suggests that the grouping of amaranths is only 164 sometimes related to their place of origin, as farmers in the region have exchanged seeds in recent years. 165 However, it is worth noting that four accessions in group II were collected from Jesús and Baños del Inca 166 districts, both in the province of Cajamarca (Figure 3). This research offers significant insights into the 167 genetic diversity of amaranths in Cajamarca, Peru, which is essential for advancing plant breeding programs. 168 The findings underscore the potential of utilizing individuals with grain color variations to develop novel 169 varieties in the agro-industry. Furthermore, it highlights the significance of categorizing accessions into 170 similar genetic and morphological groups for germplasm conservation initiatives and parent selection. 171 172 Acknowledgments

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176

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181	Competing Interests
182	All the authors declare that they have no conflicts of interest.
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184	Authors contributions
185	Lucia Emperatriz Escalante Ortiz, Jorge Luis Vasquez Orrillo, Angel Esteban Santa Cruz Padilla, and Juan
186	Francisco Seminario Cunya contributed to the study conception and design. Araceli Eugenio Leiva, Lucia
187	Emperatriz Escalante Ortiz, Jorge Luis Vasquez Orrillo, Silvia Yanina Rodriguez Lopez, and Susan Haydee
188	Soriano Morales performed material preparation, data organization, and analysis. The first draft of the
189	manuscript was written by Lucia Emperatriz Escalante Ortiz and revised by all authors. All authors read and
190	approved the final manuscript.
191	
192	Competing Interests
193	All the authors declare that they have no conflicts of interest.
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195	Data availability
196	The datasets generated during the current study are available from the corresponding author upon reasonable
197	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	Ouinua Cancha	Hualgayoc	Hualgayoc	Bambamarca	-6.67810	-78.52152	2537
24	PER2374	Covo	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	Соуо	Cajamarca	Cajamarca	Jesus	-7.24933	-78.37886	2561
30	PER2385	Соуо	Celendin	Celendín	Chogopampa	-6.91741	-78.26900	2792
31	PER2386	Соуо	Cajabamba	Cajabamba	Callash	-7.63970	-78.06299	2756
32	PER2387	Coyo Rosado	Celendin	Celendín	Sorochuco	-6.91095	-78.25475	2659
33	PER2428	Соуо	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	Соуо	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	Соуо	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	Соуо	Celendin	Celendin	Celendin	-6.86749	-78.14617	2634
52	PER2554	Соуо	Celendin	Celendin	Celendin	-6.86749	-78.14617	2634
53	PER2559	Соуо	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

304 Table 2 List of morphological descriptors used to characterize the 65 accessions of amaranths from

305 Cajamarca Region.

abbreviation acculated per evaluated per per evaluated per evaluated per e	Character	Character	States of the character	Plant phenological	Nº of plants
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 pubscence 1 genen; 2 green; 3 green Flowering 5 SC Stem color with puple-red; 8 orange-yellow Flowering 5 SS Stem shape 2 cylindrical without longitudinal stripes; 2 cylindrical with up for a longitudinal stripes; 2 cylindrical without longitudinal stripes; SS Stem shape 2 cylindrical without longitudinal stripes; 2 cylindrical without praches; 1 few branches and all near the base of the stem; 2 many Flowering 5 PBS Presence of main stem 1 lancehses and all near the base of the stem; 2 many Flowering 5 LS Leaf shape ovate; 5 rhomboid-ovate; 6 rhombic; 7 Flowering 5 LP Leaf color black; 5 puple; scale G grayish-puple; 7 Flowering 5 LP Leaf color black; 5 puple; scale G grayish-puple; 7 Flowering 5 LP Leaf olor black; 5 puple; scale G grayish-puple; 7 Flowering 5 LP Leaf olor plagitinger en;	abbreviation			stage during	evaluated per
RB SPRoot branching Stem pubescence1 low branching: 2 high branching 2 light branching: 2 high branching 1 yellowish-green: 2 green: 3 green 1 yellowish-green: 2 green: 3 green progreen-cred: 8 orange-yellow 1 cylindrical with grees stripes: 5 grayish-purple: 6 grayish-red with press stripes: 5 grayish-green with purple-red stripes: 5 grayish-grayish or purple from the underside of the grayish or purple from the underside of the gray striper: 2 green is cale 3 dark green: 4 green pigmented with red or black; 5 purple; scale 6 grayish-purple; 7 green with purple precing from with purple precing from the underside of the grayish or purple from the underside of the gray striper. 2 green with purple from the underside of the gray striper. 2 green with purple precing from the underside of the gray striper. 2 grayish-crang; 3 grayish- gray striper. 2 grayish-crang; 3 grayish- grayish-purple; 3 grayish- grayish-purpl	PH	Plant habit	1 erect; 2 semi-erect; 3 decumbent	Flowering	5
SP Stem pubescence 0 absent: 1 present Flowering 5 SC Stem color with properts 2 green: 3 green pigmented with red at the base; 4 green puple-red; 8 orange-yellow 1 e yindrical without longitudinal stripes; 2 eyindrical with superficial longitudinal stripes; 3 eyindrical with deep longitudinal stripes; 3 SS Flowering 5 SS Stem shape 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; 2 many branches and all near the base of the stem; 2 many branches and all near the base of the stem; 3 all branches and all near 1 lanccolate; 2 elliptical; 3 acuminate; 4 Flowering 5 LS Leaf shape ovate; 5 thombid-ovate; 6 frombid; 7 ovat Flowering 5 LP Leaf color black; 5 purple; scale 6 grayish-purple; 7 greens; with orange-graysh or purple bands; 8 others Flowering 5 LP Leaf color black; 5 purple; scale 6 grayish-purple; 7 greens; 2 green; with purple Flowering 5 LP Leaf olor light green; 2 green; with purple Flowering 5 LP Leaf olor light green; 2 green with purple Flowering 5 Vein prominence on VFUL the underside of the leaf I not prominent: 2 prominent Flowering 5 ID Inflorescence before maturity 1 amaranthiform; 2 clustered During physiological maturity 5 <t< td=""><td>RB</td><td>Root branching</td><td>1 low branching; 2 high branching</td><td>Flowering</td><td>5</td></t<>	RB	Root branching	1 low branching; 2 high branching	Flowering	5
SCStem coloryellowish. green; 2 green; 3 green with purple-red stripes; 5 grayish-purple; purple-red; 8 orange-yellow 1 cylindrical with out longitudinal stripes; 2 cylindrical with out longitudinal stripes; 2 cylindrical with out longitudinal stripes; 2 cylindrical with out longitudinal stripes; 0 without branches; 1 few branches and all near the base of the strams and all near the base of the strams.Flowering5LCLeaf colorblack; 5 purple; yead 6 grapish-purple; 7 grapish-purple; 7Flowering5LELeaf edge1 entire; 2 cleatate; 3 undulate the rest of the plan; 2 und thiferentiated from the rest of the plan; 2 und thiferentiated from the rest of the plan; 2 und thiferentiated from maturityBeginning of maturity </td <td>SP</td> <td>Stem pubescence</td> <td>0 absent; 1 present</td> <td>Flowering</td> <td>5</td>	SP	Stem pubescence	0 absent; 1 present	Flowering	5
SCStem colorwith red at the base; 4 green with red at the base; 4 green purple-red; 8 orange-yellow 1 cylindrical without longitudinal stripes; 2 cylindrical with superficial longitudinal stripes; 3 cylindrical with dep longitudinal stripes; 2 cylindrical with out profile without stripes; 2 cylindrical with dep longitudinal stripes; 2 cylindrical stripes; 2 cylindrical stripes; 5 machines and all near the base of the stem; 2 many branches and all near the base of the stem; 2 many branches and all near the base of the stem; 1 lancoches; 2 efficial; 3 acuminate; 4 ovate; 5 rhomboid-ovate; 6 rhombic; 7Flowering5LSLeaf shape ovat; 5 rhomboid-ovate; 6 rhombic; 7Flowering55LPLeaf pubescence 1 cyliowish- green; 2 green signented with red or green with orange-grayish or purple bands; 8 othersFlowering5LPLeaf oldge1 not prominentFlowering5VPULLeaf cdge1 not prominentFlowering5ISInflorescence type prigmentation; 2 entirely purple-red; 4 t rest of the plan; 2 not differentiated form the rest of the plan; 2 not differentiated maturity5IDInflorescence posture1 ax; 2 intermediate; 3 compact or denseDuring physiological maturity5IDInflorescence color posture1 erect; 2 seni-rect; 3 decumbent maturity1 erect; 2 seni-rec			1 yellowish- green; 2 green; 3 green		
SC Stem color with purple-red stripes; 5 grayish-purple; 6 grayish-red with green stripes; 7 purple-red; 8 orange-yellow 1 cylindrical without longitudinal stripes; 3 cylindrical with deep longitudinal stripes; 2 cylindrical with deep longitudinal stripes; 3 cylindrical with deep longitudinal stripes; 3 cylindrical with superficial longitudinal stripes; 3 cylindrical with deep longitudinal stripes; 3 cylindrical with superficial longitudinal stripes; 3 cylindrical with deep longitudinal stripes; 3 cylindrical with superficial longitudinal stripes; 3 cylindrical with deep longitudinal stripes; 4 cylindrical with superficial longitudinal stripes; 3 cylindrical with deep longitudinal stripes; 5 cylindrical with superficial longitudinal stripes; 3 cylindrical with deep longitudinal stripes; 5 cylindrical with superficial longitudinal stripes; 3 cylindrical with deep longitudinal stripes; 5 cylindrical with superficial longitudinal stripes; 5 cylindrical with deep longitudinal stripes; 5 cylindrical with superficial longitudinal stripes; 5 cylindrical with deep longitudinal stripes; 7 cylindrical with superficial longitudinal stripes; 5 cylindrical with deep longitudinal stripes; 7 cylindrical with superficial 2 cylindrical with superficial 7 cylindrical with superficial 3 acuminate; 4 react 5 due stripe; 7 cylindrical with superficial 2 cylindrical 2 cylindrical 2 cylindrical 2 cylindrical 2 cyl			pigmented with red at the base; 4 green		
SS Stem shape purple-red; 8 orange-yellow Provening 5 SS Stem shape 2 cylindrical with otep perficial longitudinal stripes; 2 cylindrical with otep perficial longitudinal stripes; 6 9 PBS Presence of main stem 0 without branches; 1 few branches and all near the base of the stem; 2 many branching on the main stem 1 lancolate; 2 ellpinical; 3 acuminate; 4 7 Flowering 5 LS Leaf shape ovat; 5 thomboid-ovate; 6 thombic; 7 Flowering 5 5 LC Leaf color black; 5 purple; scale 6 grayish-purple; 7 Flowering 5 LP Leaf pubescence 0 absent; 1 present Flowering 5 LP Leaf pubescence 0 absent; 1 present Flowering 5 LE Leaf edge 1 not prominent; 2 arent with purple 1 6 VPUL the underside of the ters of the plant; 2 nord ifferentiated from the rest of the plant; 2 nord ifferentiated from the rest of the plant; 2 condition; 3 activity purple; 7 Flowering 5 IS Inflorescence type 1 activity purple; red; 4 condifferentiated from the rest of the plant; 2 nord ifferentiated from the rest of the plant; 2 condifferentiated from the rest of the plant; 2 condifferentiated from thaurity; Begi	SC	Stem color	with purple-red stripes; 5 grayish-purple;	Flowering	5
SSStem shapepuple-red; & orange-yellow I cylindrical with superficial longitudinal stripes; 3 cylindrical with deep longitudinal stripes; 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; 2 many branches and all near the base of the stem; 2 many branches and all near the base of the stem; 2 many branches and all near the base of the stem; 2 many branches and all near the base of the stem; 2 many branches and all near the base of the stem; 2 many branches and all near the base of the stem; 2 many branches and all near the base of the stem; 2 many branches and all near the base of the stem; 2 many branches and all near the base of the stem; 2 many branches and all near the base of the stem; 2 many branches and all near the base of the stem; 2 many branches and all near the base of the stem; 2 many branches and all near the base of the stem; 2 many branches and all near the base of the stem; 2 many branches and all near the base of the stem; 2 many branches and all near the base of the stem; 2 many branches and all near the base of the stem; 2 many branches and all near the base of the stem; 2 many branches and all near the base of the stem; 2 many branches and all near the base of the stem; 2 many branches and all near the base of the stem; 2 many branches and all near the base of the stem; 2 many branches and all near the base of the stem; 2 many branches and all near the base of the stem; 2 many branches and all near the base of the stem; 2 many branches; 2 granyish-purple; 7 FloweringFlowering5LPLeaf color pigmentation; 3 entirely purple-red; 4 othersFlowering55PPetioe color			6 grayish-red with green stripes; 7		
SSStem shape1 cylindrical without longitudinal stripes; 2 cylindrical with deep longitudinal stripes; 3 cylindrical with deep longitudinal stripes; 3 cylindrical with deep longitudinal stripes; 0 without branches; 1 few branches and all near the base of the stem; 1 lanceolate; 2 elliptical; 3 cumunate; 4 oval; 5 homboid-ovate; 6 rhombic; 7 ovalFlowering5LSLeaf shape0 without branches; 1 few branches and all near the base of the stem; 1 lanceolate; 2 elliptical; 3 cumunate; 4 ovate; 5 rhomboid-ovate; 6 rhombic; 7 ovalFlowering5LCLeaf colorblack; 5 purple; calle 6 grayish-purple; 7 green with orange-grayish or purple bands; 8 othersFlowering5LPLeaf oubscence0 absent; 1 presentFlowering5LPLeaf oubescence0 absent; 1 presentFlowering5LPLeaf ouberscence0 absent; 1 presentFlowering5VPULthe underside of the leaf1 not prominent ion; 2 prominentFlowering5VPULInflorescence shape1 not prominent; 2 prominentFlowering5IDInflorescence dene posture1 erect; 2 semi-erect; 3 decumbentDuring physiological maturity5IDInflorescence color posture1 erect; 2 semi-erect; 3 decumbentDuring physiological maturity5ICBMInflorescence color at maturity1 erect; 2 grayish- orange; 4 red; 5 purple; red; 6 purple; 7 grayish- purple; 8 yellow; 3 grayish- orange; 4 red; 5 purple; red; 6 purple; 7 grayish-purple; 8 yellow; 3 grayish- orange; 4 red; 5 purple; red; 6 purple; 7 <b< td=""><td></td><td></td><td>purple-red; 8 orange-yellow</td><td></td><td></td></b<>			purple-red; 8 orange-yellow		
SSStem shape2 Cynantical with dep longitudinal stripesFlowering5PBSPresence of branching on the main stemPresence of the stem; 3 all branches and all near the base of the stem; 2 many tanches and all near the base of the stem; 3 all branches along the stem; 2 many tanches and all near the base of the stem; 3 all branches along the stem; 2 many tanches and all near the base of the stem; 3 all branches along the stem; 2 many tanches and all near the base of the stem; 3 all branches along the stem; 2 many tanches and all near the base of the stem; 3 all branches along the stem; 2 many tanches and all near the base of the stem; 3 all branches along the stem; 2 many tanches and all near the base of the stem; 3 all branches along the stem; 2 many type oval tanches and all near the base of the stem; 3 all branches along the stem; 2 many type oval tanches and all near the base of the stem; 3 all branches along the stem; 2 many type oval type ovalFlowering5LCLeaf colorbasent; 1 present pigmentation; 3 entirely purple; red; 4 othersFlowering5LPLeaf dege1 not prominent; 2 prominentFlowering5VPULthe underside of the leaf1 not prominent; 2 prominentFlowering5TInflorescence type1 terminal and well differentiated from the rest of the plant; 2 on differentiated maturityBeginning of maturity5IDInflorescence posture1 erect; 2 semi-erect; 3 decumbent range; 4 red; 5 purple; red; 6 purple; 7 grayish-purple; banks; 9 others 1 yellowish- green; 2 yellow; 3 grayish- orange; 4 red; 5 purple; red; 6 purple; 7 grayish-purple; banks; 9 o			2 cylindrical with superficial longitudinal		
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PBSPresence of branching on the main stemwithout branches; 1 few branches and all near the base of the stem; 2 many branches and all near the base of the stem; 2 many branches and lanear the base of the stem; 3 all branches along the stem 1 hanceolate; 2 elliptical; 3 acuminate; 4 oval: 3 acuminate; 4Flowering5LSLeaf shapeovate; 5 rhomboid-ovate; 6 rhombic; 7 oval 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 othersFlowering5LPLeaf colorblack; 1 present 1 light green; 2 green with purple pigmentation; 3 entirely purple- red; 4Flowering5PCPetiole colorpigmentation; 3 entirely purple- red; 4Flowering5VPULthe underside of the leaf1 not prominent; 2 prominentFlowering5ITInflorescence others1 amaranthiform; 2 clusteredDuring physiological maturity5IDInflorescence other orange; 4 red; 5 purple; red; 3 dcumbent posture1 lear; 2 intermediate; 3 compact or denseDuring physiological maturity5ICBMInflorescence color before maturity1 lax; 2 intermediate; 3 compact or denseDuring physiological maturity5ICMInflorescence color at maturity1 learce; 2 semi-ered; 3 dcumbent purple bands; 9 othersDuring physiological maturity5ICBMInflorescence color at maturity1 learce; 2 semi-ered; 6 purple; 7 grayish-purple; 8 yellowish-green with purple bands; 9 othersDuring physiological maturi			longitudinal stripes		
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LSLeaf shapeovate; 5 thomboid-ovate; 6 thombie; 7Flowering5oval1 yellowish- green; 2 green; scale 3 dark green; 4 green pigmented with red orFlowering5LCLeaf colorblack; 5 purple; scale 6 grayish-purple; 7 green with orange-grayish or purple bands; 8 othersFlowering5LPLeaf pubescence0 absent; 1 presentFlowering5LELeaf edge1 entire; 2 dentate; 3 undulateFlowering5PCPetiole colorpigmentation; 3 entirely purple- red; 4 othersFlowering5VPULthe underside of the leaf1 not prominent; 2 prominentFlowering5ITInflorescence type1 terminal and well differentiated from the rest of the plant; 2 not differentiatedBeginning of physiological maturity5IDInflorescence density1 lax; 2 intermediate; 3 compact or denseDuring physiological maturity5IDInflorescence color posture1 erect; 2 semi-erect; 3 decumbent maturityDuring physiological maturity5ICBMInflorescence color at maturity1 lax; 2 intermediate; 3 compact or denseDuring physiological maturity5ICMInflorescence color at maturity1 yellowish- green; 2 yellow; 3 grayish- orange; 4 red; 5 purple - red; 6 purple; 7 grayish- purple; 8 yellowish- green with purple bands; 9 othersDuring physiological maturity5ICMInflorescence color at maturity1 rect; 5 purple - red; 6 purple; 7 grayish- purple; 8 yellowish- green with purple bands; 9		main stem	stem; 3 all branches along the stem		
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LCLeaf colorDefinition for green i general with red or bands; 8 othersLPLeaf pubescence0 absent; 1 presentFloweringLELeaf edge1 entire; 2 dentate; 3 undulateFloweringPCPetiole colorpigmentation; 3 entirely purple- red; 4FloweringPCPetiole colorpigmentation; 3 entirely purple- red; 4FloweringVein prominence on the underside of the leaf1 not prominent; 2 prominentFloweringTInflorescence type1 terminal and well differentiated from the rest of the plant; 2 not differentiated maturityBeginning of physiological maturityIDInflorescence shape1 amaranthiform; 2 clusteredDuring physiological maturityIDInflorescence density1 lax; 2 intermediate; 3 compact or dense densityDuring physiological maturityIPInflorescence orange; 4 red; 5 purple- red; 6 purple; 7 grayish-purple; 8 yellowish-green; 2 yellow; 3 greyish- orange; 4 red; 5 purple- red; 6 purple; 7 grayish-purple; 8 yellowish-green with purple bands; 9 othersFloweringICMInflorescence color at maturityInflorescence color orange; 4 red; 5 purple- red; 6 purple; 7 grayish-purple; 8 yellowish-green with purple bands; 9 othersDuring physiological maturityICMInflorescence color at maturityInflorescence color orange; 4 red; 5 purple- red; 6 purple; 7 grayish-purple; 8 yellowish-green with purple bands; 9 othersDuring physiological maturityGCGrain color1 orange-white; 2 grayish-orange; 3 opaqueAfter harvest5 <td></td> <td></td> <td>OVal 1 vallowish green: 2 green: scale 3 dark</td> <td></td> <td></td>			OVal 1 vallowish green: 2 green: scale 3 dark		
LCLeaf colorblack is purple; scale 6 grayish-purple; 7 green with orange-grayish or purple bands; 8 othersFlowering5LPLeaf pubescence o absent; 1 presentFlowering5LELeaf edge1 entire; 2 dentate; 3 undulateFlowering5PCPetiole colorpigmentation; 3 entirely purple- red; 4 			green: 4 green nigmented with red or		
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306 307	The color of the stem, leaf, inflorescence, and seed was recorded using the color chart of the Royal
308	Horticultural Society.
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Table 3 Main components, eigenvalues and proportion of total variance explained by the first six principal

331 components of 65 amaranth accessions from the Cajamarca region, characterized by 21 morphological

- descriptors.
- 333

Main component	tes 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	
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347 Table 4 Six principal components, proportion of total variance, traits, and correlation coefficients in the

	Characters	Correlation coefficient
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
40.381	Stem color (SC)	0.509
	Inflorescence type (IT)	0.781
	Leaf shape (LS)	0.689
	Vein prominence on the underside of the leaf	0.683
50.362	(VPUL)	0.005
	Inflorescence shape (IS)	0.615
58.711	Grain Type (GT)	0.714
	Stem shape (SS)	0.613
	Grain shape (GS)	0.587
66 024	Inflorescence posture (IP)	0 576
00.021	Presence of branching on the main stem (PBS)	0.561
70.838	Root branching (RB)	0.665
	Stem pubescence (SP)	0.5051
	40.381 50.362 58.711 66.024 70.838	Inflorescence color before physiological maturity (ICBM)Inflorescence color at maturity (ICM)Petiole color (PC) Stem color (SC) Leaf edge (LE) Stem pubescence (SP)40.381Stem color (SC) Inflorescence type (IT) Leaf shape (LS) Vein prominence on the underside of the leaf50.362(VPUL)58.711Grain Type (GT) Stem shape (SS) Grain shape (GS)66.024Inflorescence posture (IP) Presence of branching on the main stem (PBS)70.838Root branching (RB) Stem pubescence (SP)



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



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

