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Original Article

Interpopulation characterization of quinoa (*Chenopodium quinoa* Willd.) from different agroecological environments of Colombia

Caracterização interpopulacional de quinoa (*Chenopodium quinoa* Willd.) de diferentes ambientes agroecológicos da Colômbia

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Abstract

Chenopodium quinoa Willd. it is an Andean cereal of great importance for human consumption due to its high nutritional value. In Colombia there is a high phenotypic and genotypic variability within quinoa crops, which has not been studied and has been maintained by the same farmers cycle after production cycle. The objective of this study was to carry out an interpopulation characterization of quinoa cultivated in different producing municipalities of the department of Boyacá, in Colombia, for which 19 morphological descriptors were used, which were evaluated *in situ* in nine municipalities and analyzed through descriptive statistics, principal component analysis, correlation and conglomerates. In the evaluation of the quantitative traits for all the populations, it was observed that the most variable descriptors were Number of teeth lower leaf (DHI), Lower leaf length (LHI), Width upper leaf (AHI) and Number of teeth upper leaf (DHS). Great segregation between and within individuals of Blanca de Jericó and Piartal was observed for panicle and leaf color and shape, stem color, presence of teeth, and axils on upper and lower leaves. A classification key is proposed that allows in the field to be able to morphologically differentiate the genotypes of Piartal and Blanca de Jericó. This research shows that among the most cultivated genotypes in the department of Boyacá, there is still an important phenotypic diversity given at the inter and intra-individual level, due to the phenological state and the agroclimatological conditions of the different producing regions.

Keywords: andean cereal, morphological descriptors, germplasm, breeding.

Resumo

Chenopodium quinoa Willd. é um cereal andino de grande importância para a alimentação humana por causa do seu alto valor nutricional. Na Colômbia, existe uma alta variabilidade fenotípica e genotípica nos cultivos de quinoa, que não foi estudada e tem sido mantida pelo mesmo produtor ciclo após ciclo de produção. O objetivo deste estudo foi realizar uma caracterização interpopulacional da quinoa cultivada em diferentes municípios produtores do departamento de Boyacá, na Colômbia. Para tanto, foram utilizados 19 descritores morfológicos, avaliados *in situ* em nove municípios e analisados por meio de estatísticas descritivas, análise de componentes principais, correlação e conglomerados. Na avaliação dos caracteres quantitativos para todas as populações, observou-se que os descritores mais variáveis foram: número de dentes da folha inferior (DHI), comprimento da folha inferior (LHI), largura da folha superior (AHI) e número de dentes da folha superior (DHS). Entre os indivíduos de Blanca de Jericó e Piartal e dentro deles, observou-se grande segregação quanto à cor, formato da panícula e folha, cor do caule, presença de dentes e axilas nas folhas superiores e inferiores. É proposta uma chave de classificação que permite no campo poder diferenciar morfologicamente os genótipos de Piartal e Blanca de Jericó. Esta pesquisa mostra que, entre os genótipos mais cultivados no departamento de Boyacá, ainda existe uma importante diversidade fenotípica em nível inter e intraindividual, em razão do estado fenológico e das condições agroclimatológicas das diferentes regiões produtoras.

Palavras-chave: cereal andino, descritores morfológicos, germoplasma, melhoramento.

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1. Introduction

Quinoa (*Chenopodium quinoa* Willd.) is an annual species, native to South America, with wide agroecological adaptation, cultivated mainly in countries such as Chile, Bolivia, Ecuador, Peru and Colombia, in the latter especially in the departments of Nariño, Cauca, Boyacá and Cundinamarca (Information and Communication Network of the Colombian Agricultural Sector, Agronet, 2022), where every day the planting areas have increased due to the agronomic and commercialization potential of products derived from quinoa (Alandia et al., 2020). Worldwide, it is considered a species with high nutritional value, due to its content of essential amino acids, proteins, vitamins and antioxidant properties (El-Hackim et al., 2022). Its seeds contain saponins, a secondary metabolite with potential use in industry and medicine (El Hazzam et al., 2020; Morillo et al., 2022a). It has a high genetic diversity in its phenotypic and genotypic characteristics, as a result of its reproduction, adaptation and domestication process (Abdelaleem and Elbassiony, 2021; Hafeez et al., 2022).

Within the studies of genetic diversity of germplasm, it has been determined that both inter and intraspecific variation contribute to the total biodiversity observed and quantified in both plants and animals (Liu et al., 2022). Although quinoa is considered a preferably autogamous species, it shows notable inter- and intra-population genetic variation, which is easily observable within cultivated fields, and quantifiable through morphological, biochemical, and molecular markers (Del Castillo Gutierrez and Winkel, 2014).

Farmers classify quinoa according to the content of saponins in the grain, into sweet and bitter. The Blanca de Jericó and Piartal genotypes belong to the group of sweet Quinoas. Blanca de Jericó comes from the department of Boyacá, it is tall, semi-late, with open ramification from the base and a white panicle; For its part, the Piartal genotype is native to northern Ecuador, purple in color, is approximately 240 cm tall and is susceptible to mildew. The grain is opaque white, 2 mm in diameter (Morillo et al., 2022b).

In Colombia, there have been morphoagronomic characterization studies on quinoa materials cultivated on the Bogotá savanna and in Nariño (García et al., 2018). In Boyacá, Morillo et al. (2020) evaluated 19 quinoa materials in the department of Boyacá with 27 morphological descriptors. Other studies have reported a mixture of the genotypes in the crops (Manjarres et al., 2021a, 2021b), the results of these studies showed that the evaluated genotypes present great variability in both qualitative and quantitative characteristics, which can be used for the selection of materials (Morillo et al., 2022a, b).

However, there are few studies that try to explain how the distribution of genetic variation is at different levels of organization of the species, for which the objective of this research was to characterize the intrapopulation morphoagronomic diversity in two genotypes of quinoa (*C. quinoa*). in the department of Boyacá using morphological descriptors to analyze their variation, with a view to establishing improvement strategies that lead to obtaining quinoa varieties that meet the needs of the farmer, producer and consumer.

2. Material and Methods

2.1. Vegetal material

We evaluated Fifty-four different morphotypes selected in already established crops of Blanca de Jericó and Piartal quinoa cultivars in the municipalities of Tuta, Siachoque, Sogamoso, Monguí, Tunja and Combita, belonging to the department of Boyacá. In the field, a simple stratified and random sampling was used, through which the plants that presented phenotypic variation in terms of panicle color, presence of axillae and pigmented striae (morphotypes) were identified; the number of replicates depended on the number of different morphotypes found in the crops. For this interpopulation study, the populations were defined according to the genetic material and the locality where the crops were established, for a total of nine populations (Table 1).

2.2. Morphoagronomic characterization

We evaluated 11 qualitative and eight quantitative descriptors (Table 2) *in situ* at physiological maturity in 54 morphotypes to Blanca de Jericó and Piartal from six municipalities. These descriptors have been used

Table 1. Geographical location of Blanca de Jericó and Piartal quinoa collection sites.

Population	Municipality	Coordinates	Cultivar	Morphotypes
1	Tuta	5°39´53.3´´N - 73°10´13.9´´W	Blanca de Jericó	15
2	Siachoque	5°30´0.6´´N - 73°29´52.6´´W	Piartal	3
3	Sogamoso	5° 40´41" N - 72° 56´ 38"W	Piartal	6
4	Monguí	5°43′21″N - 72°50′57″W	Piartal	6
5	Tunja	5°33′16″N - 73°21′09″W	Blanca de Jericó	6
6	Tunja	5°33′16″N - 73°21′09″W	Piartal	6
7	Combita	5°38′02″N - 73°19′23″W	Piartal	6
8	Siachoque	5°30´0.6´´N - 73°29´52.6´´W	Blanca de Jericó	6
9	Porvenir	5°31´06.1´´N - 73°23´47.1´´W	Blanca de Jericó	6

Table 2. Morphological descriptors used for the morphological characterization of Blanca de Jericó and Piartal genotypes.

Qualitative	Quantitative
Panicel color at physiological maturity (CP)	Plant height (cm) (AP)
Panicle shape (FP)	Main stem diameter (cm) (DT)
Steam color (CT)	Panicle length (cm) (LP)
Upper and lower leaf color (CHS)	Panicle diameter (cm) (DP)
Upper and lower leaf shape (FHS)	Number of teeth upper leaf (DHS)
Upper and lower leaf edge (BHS)	Number of teeth lower leaf (DHI)
Presence of teeth on upper leaf (PDS)	Upper leaf length (LHS) and width (AHS)
Presence of teeth on lower leaf (PDI)	Length (LHI) and width of lower leaves (AHI)
Presence of pigmented axillae (PA)	
Growth habit (HC)	
Striae color (CE)	

successfully in the evaluation of quinoa germplasm in Colombia (Manjarres et al., 2021a, b; Morillo et al., 2022b).

2.3. Data analysis

With the data obtained from the morphoagronomic characterization of the qualitative descriptors FP, CP, CT, CHS, FHS, BHS, PDS, PDI, PA, HC, CE and quantitative AP, DT, LP, DP, a multivariate scaling analysis was performed non-metric multidimensional (NMDS) with the Gower method, in order to graphically represent the relationships between populations (Trevor, 2001), using the PAST statistical program (3.26b). A cluster analysis was made with the Ward method considering the squared Euclidean distance to estimate the similarity or difference between the evaluated populations, using the R program (4.1.1); the Ward method unites the cases seeking to minimize the variance within each group; this procedure creates homogeneous groups with similar sizes. Pearson correlation analyzes were performed between the variables evaluated in all populations.

The qualitative descriptors were coded for the management of different states of a character for different plants of the same population; each population was coded according to the state(s) in which each character is found in its plants and thus characterize an OTU (Operative Taxonomic Unit, each population for this case); all the plants of all the populations have the angular Stem Shape and the Presence of Stretch Marks present, thus, they are not included in the analysis because they are uniform. Each of the individuals in each population are spatially represented by points on the two-dimensional graph.

Considering the qualitative and quantitative characters, the authors propose a dichotomous classification for the identification of quinoa morphotypes present in quinoa crops in Colombia. Analysis of variance was performed to establish the significance of the variables evaluated. These analyzes were carried out with the statistical software SAS. 9.0.

3. Results

In this study, the populations of the Blanca de Jericó and Piartal cultivars to be evaluated were defined according to the phenotypic differences observed in the plants, such as panicle color, presence or absence of axils and pigmented streaks, established in the productive systems present in the municipalities of Tuta, Siachoque, Sogamoso, Monguí, Tunja, and Cómbita, thus defining new populations.

In the evaluation of the quantitative characteristics for all the populations, it was observed that the most variable descriptors were DHI (89%), LHI (80%), AHI (82%) and DHS (58%). The least variable characteristic was panicle length (LP) with a coefficient of variation of 19% and a range between 12 and 39 cm (Table 3). For the Blanca de Jericó genotype, it was found that in all populations (P1, P5, P8 and P9) the most variable quantitative descriptors were those associated with leaf diameter, length and width with coefficients of variation greater than 90% (P1 and P8). The Analysis of Variance detected statistically significant differences ($p<0.05$) between the evaluated morphotypes of Blanca Jericó for the characteristics of plant height, stem diameter, panicle length and diameter, number of panicles, and number of teeth on the leaves (Table 3).

The Principal Component Analysis grouped the 10 quantitative variables into the first two components (CP1 and CP2), which explain more than 70% of the phenotypic variation observed in the Blanca de Jericó morphotypes evaluated in the different municipalities. All variables contribute significantly to each of the components (Figure 1).

Regarding the evaluation of the qualitative characteristics in the populations of the Blanca de Jericó genotype, it was

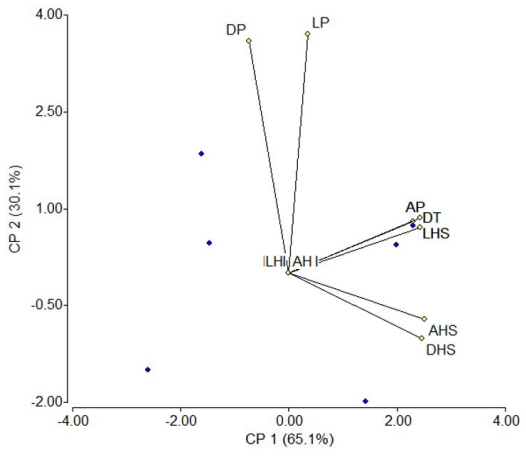

Figure 1. Principal Components Analysis for the quantitative characteristics evaluated in the morphotypes of Blanca de Jericó quinoa in the department of Boyacá.

Table 3. Descriptive statistics of the quantitative morphological variables and main components for the Blanca Jericó.

P1								P5							
Variable	**N**	**Average**	**S.D**	**C.V (%)**	**Range**	**CP1**	**CP2**	**Variable**	**N**	**Average**	**S.D**	**C.V (%)**	**Range**	**CP1**	**CP2**
AP	5	114.0	12.60	11.04	27	0.89	-0.09	**AP**	6	135.33	8.76	6.47	24	0.81	0.32
DT	5	3.60	0.47	13.18	1.1	0.89	-0.18	**DT**	6	5.18	0.68	13	1.9	0.46	0.25
LP	5	25.80	4.15	16.00	9.9	0.41	-0.81	**LP**	6	22.40	5.43	24.25	13.6	-0.47	0.87
DP	5	27.43	4.97	15,10	13.3	-0.35	-0.89	**DP**	6	30.46	5.45	17.88	14.25	-0.43	0.56
DHS	5	23.46	13.89	59,19	34.3	0.05	0.11	**DHS**	6	15.67	4.27	27.28	10	0.77	0.55
DHI	5	15.14	15.74	103.96	34.7	-0.24	0.96	**DHI**	6	14.67	4.13	28.17	12	0.78	-0.59
LHI	5	4.76	0.79	16.65	1.9	0.84	0.46	**LHI**	6	3.82	0.51	13.30	0.6	0.02	-0.78
AHI	5	4.34	0.95	21.90	2	0.97	0.20	**AHI**	6	3	0.29	9.48	0.9	0.04	-0.11
LHS	5	7.38	1.00	14.32	2.6	0.97	0.17	**LHS**	6	5.18	0.77	14.76	2	0.87	0.01
AHS	5	5.52	1.12	20.27	2.8	0.92	-0.28	**AHS**	6	1.82	0.51	10.62	0.5	0.71	0.46
P8								**P9**							
AP	7	90.57	7.39	8.16	20	0.08	0.55	**AP**	9	84.89	16.45	19.38	51	0.34	0.52
DT	7	3.01	0.29	9.47	0.9	0.49	-0.51	**DT**	9	3.71	0.69	18.59	2.48	0.07	0.76
LP	7	28.47	5.39	18.94	16.48	-0.22	-0.89	**LP**	9	27	5.88	21.2	16.5	0.47	0.34
DP	7	27.89	7.24	25.96	19.44	-0.77	0.01	**DP**	9	25.73	5.6	22.7	17.6	0.04	-0.53
DHS	7	28.71	6.85	23.85	20	0.04	0.96	**DHS**	9	21.3	4	18.75	14	0.67	-0.46
DHI	7	18.86	17.96	95.23	38	-0.59	0.03	**DHI**	9	17	4.9	28.26	14	0.86	-0.35
LHI	7	4.61	0.64	13.90	1.7	0.80	-0.14	**LHI**	9	2.61	0.4	15.13	1.5	0.93	-0.19
AHI	7	3.93	0.88	22.27	2.5	0.79	-0.43	**AHI**	9	2.20	0.36	16.55	1.2	0.90	-0.22
LHS	7	7.21	1.39	19.25	3.4	0.85	0.24	**LHS**	9	3.38	0.80	23.58	2.5	0.64	0.42
AHS	7	5.4	1.43	26.43	3	0.92	0.26	**AHS**	9	2.82	0.56	19.87	1.8	0.52	0.64

AP: Plant height; **DT:** Main stem diameter; **LP:** Panicle length; **DP:** Panicle diameter; **DHS:** Number of teeth upper leaf; **DHI:** Number of teeth lower; **LHI:** Lower leaf length; **AHI:** Lower leaf width; **LHS:** Upper leaf length; **AHS**: Upper leaf width; **N:** Number of morphotypes in each population; **SD:** Standard deviation; **CV:** Coefficient of variation; **CP1:** Principal component one; **CP2:** Principal component two.

possible to observe phenotypic variation for populations 1 and 9 for the color of the green, light purple, and purple panicle, in all populations around 9% of the individuals had green panicles and 43% purple. All P5 morphotypes were green. The color of the stem of P5 and P9 was only green, while in P1 and P8 there were colors between yellow, green and purple. For P1 and P8, the qualitative variation occurred mainly in characteristics such as the edge of the leaves (serrated, teethed and entire), while in P5 only sawn and dentated edges were present, while in P9 some upper and lower leaves showed serrated edges.

In all the populations evaluated, the lower leaves and the streaks presented colors between green-yellow, yellow and green. The color of the axillae was purple for all the populations except P5, where 50% of the individuals had purple axillae and the other 50% had pigmented axillae. In general, the less variable qualitative characteristics in all the evaluated populations of Blanca de Jericó were the shape of the stem (angular), the color of the upper leaves (between green and green-yellow); The shape of the upper and lower leaves was rhomboid or triangular, with a simple growth habit and green striations. In general, the less variable qualitative characteristics in all the evaluated populations of Blanca de Jericó were the shape of the stem (angular), the color of the upper leaves (between green and green-yellow); The shape of the upper and lower leaves was rhomboid or triangular, with a simple growth habit and green strias.

Among the evaluated individuals from Piartal, it was found that the most variable qualitative characteristic was the color of the panicle, with P1, P4 and P7 being the populations that showed a 1:1 segregation between green and purple, all P2 individuals exhibiting a purple color and P6 green. The shape of the panicle for P1 was 100% glomerulate, in P5 intermediate and amarantiform and simple for the rest of the evaluated populations (P1, P4 and P6). It was observed that the edge of the leaf was serrated and teethed for populations P1, P6 and P7, and 100% serrated for P1 and 50% entire and 50% serrated for P3. In the characteristic presence of pigmented axillae, it was found that individuals in P2 had no axillae, P7 had axillae but not pigmented, P1 was 50% purple and 50% no axillae, and P6 had 50% purple and 50% no pigmentation. The color of the stem was between green and yellow tones. Populations P1, P4 and P7 presented defoliation on the lower leaves, and a green-yellow color on the upper leaves. In general terms, it was observed that most of the Piartal individuals showed leaf shapes between rhomboid and triangular, presence of teeth on the upper and lower leaves, angular stem, simple growth habit, green striations, except for P7 that presented strias red.

In the morphoagronomic evaluation of the five populations of Piartal quinoa in the department of Boyacá, it was found that the most variable quantitative descriptors were DHS (24-110%, P2 and P4, respectively), DHI (28% P6), AHI (27% P7), AHS (15-113%, P3 and P4, respectively), LHI (23% P2), LP (25-31% P6 and P3, respectively), DP (34% P3) and AP (22% P2) (Table 4). In the Principal Components Analysis, it was observed that the first two components, CP1 and CP2, explained more than 70% of the total observed phenotypic variation within Piartal genotypes, and there was a significant contribution from all variables to the two components, except those characteristics related to the lower leaves, where populations P3, P4 and P6 presented defoliation during the evaluation period (Figure 2). Characteristics such as AP (16.6-17.7 cm) and DT (1.33-4.35 cm) obtained similar values to those reported in other studies of genetic diversity of quinoa germplasm in Colombia.

Among the evaluated individuals from Piartal, it was found that the most variable qualitative characteristic was the color of the panicle, with P2, P6 and P7 being the populations that showed a 1:1 segregation between green and purple, all P3 individuals exhibiting a purple color and P6 green. The shape of the panicle for P2 was 100% glomerulate, in P7 intermediate and amarantiform and simple for the rest of the evaluated populations (P2, P6 and P7). It was observed that the edge of the leaf was serrated and teethed for populations P2, P6 and P7, and 100% serrated for P1 and 50% entire and 50% serrated for P3. In the characteristic presence of pigmented axillae, it was found that individuals in P2 had no axillae, P7 had axillae but not pigmented, P2 was 50% purple and 50% no axillae, and P6 had 50% purple and 50% no pigmentation. The color of the stem was between green and yellow tones. Populations P1, P4 and P7 presented defoliation on the lower leaves, and a green-yellow color on the upper leaves. In general terms, it was observed that most of the Piartal individuals showed leaf shapes between rhomboid and triangular, presence of teeth on the upper and lower leaves, angular stem, simple growth habit, green striations, except for P7 that presented strias red.

Table 5 presents the Pearson correlation matrix between each pair of variables evaluated in all populations, where the positive and more significant associations were AHS and LHS (r=0.91), AHI and LHI (0.88), AP and DT (r=0.91), and DHI and DHS (r=0.78), and there were significant negative associations for LHS and LP (r=-0.81) and AHS and LP (r= -0.81). In general, the results showed a significant correlation between AP and DT and AHS and LHS for all populations.

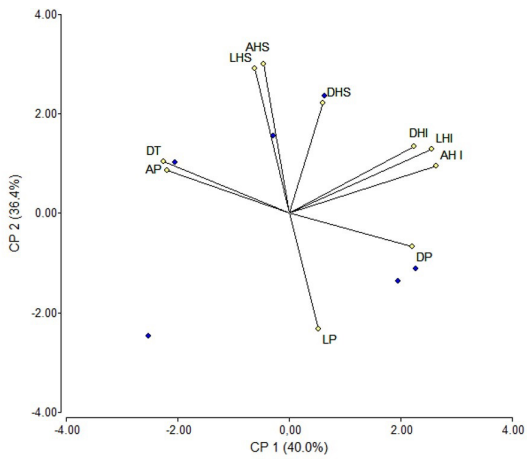

Figure 2. Principal Components Analysis for the quantitative characteristics evaluated in the morphotypes of Piartal quinoa in the department of Boyacá.

Table 4. Descriptive statistics of the quantative morphological variables and main components for the Piartal genotypes.

P2								P7							
Variable	**N**	**Average**	**S.D**	**C.V (%)**	**Range**	**CP1**	**CP2**	**Variable**	**N**	**Average**	**S.D**	**C.V (%)**	**Range**	**CP1**	**CP2**
AP	3	77.33	1.21	22.26	32	0.95	-0.31	**AP**	6	177.33	29.87	16.84	90	-0.75	0.28
DT	3	3.97	0.25	6.34	0.5	-1	0.05	**DT**	6	4.5	0.81	17.94	2.5	-0.77	0.34
LP	3	27.92	1.47.	5.27	2.95	0.98	0.19	**LP**	6	26.35	6.48	24.58	17.9	0.18	-0.76
DP	3	24.44	4.46	18.25	8.91	1	0.03	**DP**	6	20	1.54	7.68	4.3	0.75	-0.22
DHS	3	15.53	3.66	23.53	7.3	0.4	0.92	**DHS**	6	10.33	6.38	61.71	18	0.21	0.72
DHI	3	23.30	4	17.17	8	0.45	0.89	**DHI**	6	11	6.16	56	16	0.76	0.44
LHI	3	4.47	1	22.54	2	-0.64	0.77	**LHI**	6	5.55	1	18.68	2.5	0.87	0.42
AHI	3	4	047	11.72	0.9	-0.97	0.25	**AHI**	6	4.78	1.27	26.62	2.8	0.90	0.31
LHS	3	7.27	0.40	5.56	0.7	0.83	0.55	**LHS**	6	5.95	1	16.73	2.2	-0.21	0.95
AHS	3	5.37	0.76	14.23	1.5	-0.38	0.92	**AHS**	6	4.87	1	21.54	2.2	-0.16	0.98
P3								**P4**							
AP	6	166.50	20.42	12.27	55	-0.68	0.71	**AP**	6	160	21.84	13.65	60	0.89	0.21
DT	6	4.15	0.72	17.29	1,7	-0.68	0.66	**DT**	6	4.28	0.79	18.41	2.1	0.95	0.23
LP	6	29.27	9.14	31.23	27	-0.77	0.09	**LP**	6	28.13	3.85	13.70	9.7	0.13	0.98
DP	6	28.98	9.72	33.52	27	-0.81	0.35	**DP**	6	24.28	3	12.36	8.4	0.29	0.95
DHS	6	7.33	8	110	16	0.85	0.48	**DHS**	6	9	9.94	110.44	20	0.96	0.27
LHS	6	2	2.38	114	5	0.87	0.49	**LHS**	6	2.75	0.52	1.9	1.5	0.95	0.19
AHS	6	1.33	1.51	112.9	3	0.85	0.52	**AHS**	6	1.77	0.26	14.62	0.5	0.98	0.19

P6							
Variable	**N**	**Average**	**S.D**	**C.V (%)**	**Range**	**CP1**	**CP2**
AP	6	132	30.38	23	90	0.83	-0.35
DT	6	7	0.92	13	2.5	-0.66	0.47
LP	6	31.18	3.60	11.53	10	0.96	0.16
DP	6	30.55	5	16.41	13.6	-0.16	0.09
DHS	6	16	3.58	22.36	10	0.71	0.69
LHS	6	3.6	0.53	14.80	1.3	0.82	0.39
AHS	6	2.58	0.70	26.98	1.5	0.78	-0.32

AP: Plant height; **DT:** Main stem diameter; **LP:** Panicle length; **DP:** Panicle diameter; **DHS:** Number of teeth upper leaf; **DHI:** Number of teeth lower; **LHI:** Lower leaf length; **AHI:** Lower leaf width; **LHS:** Upper leaf length; **AHS**: Upper leaf width; **N:** Number of morphotypes in each population; **SD:** Standard deviation; **CV:** Coefficient of variation; **CP1:** Principal component one; **CP2:** Principal component two.

In the NMDS analysis populations are described by location and material type with the population number designated: We can see that Combita-Piartal (C_P_7) is different from the others; Sogamoso-Piartal (S_P_3) and Mongui-Piartal (M_P_4) share characteristics that make them group together; Tuta-Blanca de Jericó (T_BJ_1) and Siachoque-Blanca de Jericó (Si_BJ_8) are similar; the María Blanca de Jericó (LM_BJ_5) and the María-Piartal (LM_P_6) are very similar because they are very close; Porvenir-Blanca de Jericó (P_BJ_9) and Siachoque-Piartal (Si_P_2) are similar; these last four share some morphological characters that may be influencing the groupings (Figure 3). However, this is corroborated by the Cluster Analyses. The cluster analysis shows the distribution of the morphotypes of Blanca de Jericó and Piartal according to the qualitative and quantitative descriptors evaluated. Thus, the population of Combita-Piartal-7 is the most different from the others, and Mongui-Piartal-4 and Sogamoso-Piartal-3 seem to be the most similar (Figure 4).

Two groups of populations were formed: group 1 with Panicle Diameter < 21.88 +/- 1.18 cm, Panicle Shape: glomerulate, intermediate, amarantiform (7), Upper Leaves Color: green, green-yellow (3), Habit of Growth: simple, branched up to the lower third (4), Color of Striae: yellow (2) that characterize and differentiate the Combita-Piartal-7 population from the other populations, and the other group of populations (group 2: Mongui- 4, Sogamoso-3, Tuta-1, Siachoque-8, La Maria-5, La Maria-6, Porvenir-9, Siachoque-2) have Panicle Diameter > 21.88 +/- 1.18 cm, Panicle Shape: glomerulate (1), Color

Table 5. Pearson correlation analysis for the quantitative variables (P≥ 0.001) in the all populations.

	AP	DT	LP	DP	DHS	DHI	LHI	AHI	LHS	AHS
AP	1									
DT	0.91**	1								
LP	0.70	0.78	1							
DP	0.04	0.03	0,17	1						
DHS	0.46	0,39	0.87	0,12	1					
DHI	0.02	0,07	0.09	0.58	0.78	1				
LHI	0,05	0,50	0.23	0.53	-0.11	0.70	1			
AHI	0.17	0,49	0.10	0.59	-0.37	0.73	0.88**	1		
LHS	0.10	0,52	-0.81*	0.51	0.33	0.37	0.60	0.44	1	
AHS	0.20	0.34	-0.81*	0.73	0.29	0.66	0.54	0.49	0.91**	1

AP: Plant height; **DT:** Main stem diameter; **LP:** Panicle length; **DP:** Panicle diameter; **DHS:** Number of teeth upper leaf; **DHI:** Number of teeth lower; **LHI:** Lower leaf length; **AHI:** Lower leaf width; **LHS:** Upper leaf length; **AHS:** Upper leaf width. **Highly significant. *Significant.

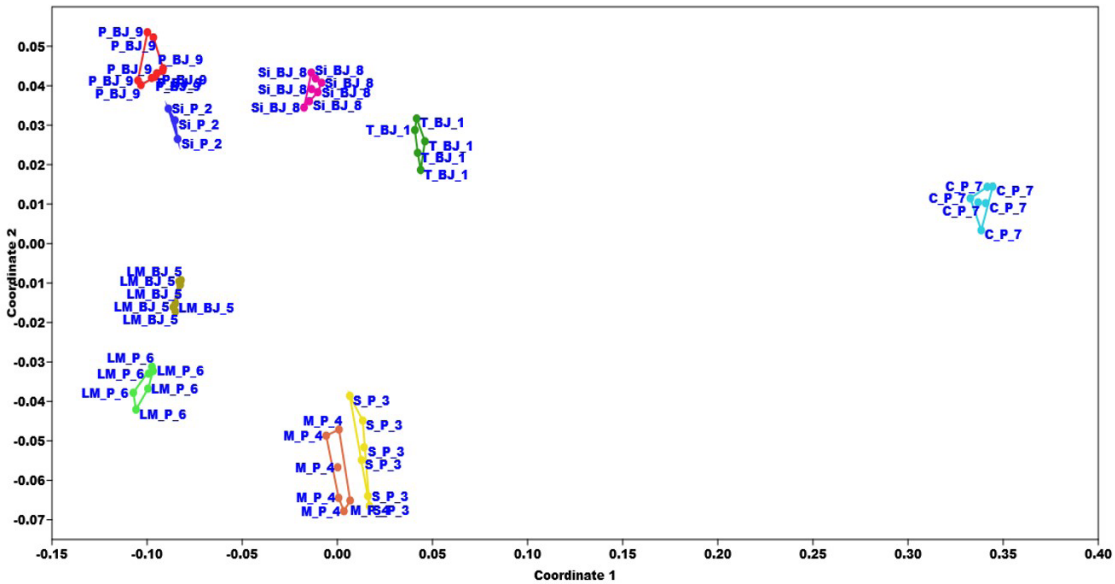

Figure 3. NMDS analysis for the nine quinoa populations: Combita-Piartal (C_P_7); Sogamoso-Piartal (S_P_3); Mongui-Piartal (M_P_4); Tuta- White of Jericó (T_BJ_1); Siachoque-Blanca de Jericó (Si_BJ_8); La María Blanca de Jericó (LM_BJ_5) and La María-Piartal (LM_P_6); Porvenir- Blanca de Jericó (P_BJ_9) and Siachoque-Piartal (Si_P_2).

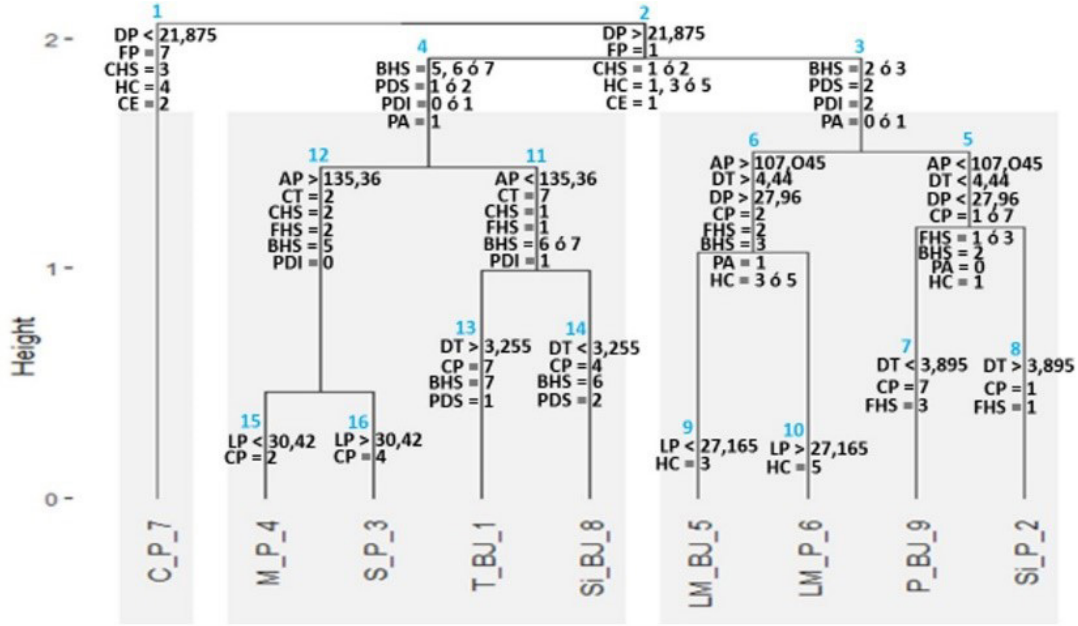

Figure 4. Dendrogram of the hierarchical classification analysis for the Blanca de Jericó and Piartal quinoa evaluated in the department of Boyacá, Colombia.

Upper Leaves: green (1) or green-yellow (2), Growth Habit: simple (1), branched up to the second third (3), or simple and branched up to the second third (5), Color of Stretch Marks: green (1).

Group 2 is subdivided into two groups, the first on the right (group 3) with Upper Leaf Edge: serrated (2) or serrated (3), Presence of Upper Leaf Teeth: present (2), Presence of Lower Leaf Teeth: present (2), Presence of Armpits: absent (0), or absent or present (1) that characterize the populations La María-Blanca de Jericó-5, La María-Piartal-6, Porvenir-Blanca de Jericó-9, Siachoque-Piartal-2; the second on the left (group 4) with BHS = 5, 6 or 7, PDS = 1 or 2, PDI = 0 or 1, Presence of Axillae: absent or present (1) that characterize the Monguí-Piartal-4 populations, Sogamoso-Piartal-3, Tuta-Blanca de Jericó-1, Siachoque-Blanca de Jerico-8.

Group 3 is subdivided into two groups: the first (group 5) with Plant Height < 107.05 +/- 16.68 cm, Stem Diameter < 4.44 +/- 0.39 cm, Panicle Diameter < 27.97 +/- 0.28 cm, Panicle Color: purple (1), or, purple, green or other (7), Shape of Upper Leaves: rhomboid (1), or, rhomboid or triangular (3), Upper Leaf Edge: dentate (2), Presence of pigmented Axils: absent (0), Growth Habit: simple (1) that characterize the Porvenir-Blanca populations of Jerico-9, Siachoque-Piartal-2; the second group (group 6) with Plant Height > 107.05 +/- 16.68 cm, Stem Diameter > 4.44 +/- 0.39 cm, Panicle Diameter > 27.97 +/- 0.28 cm, Panicle Color: green (2), Shape of Upper Leaves: triangular (2), Edge of Upper Leaves: serrate (3), Presence of pigmented Axils: present (1), Growth Habit: branched up to second third (3), or, simple or branched to the second third (5) that characterize the populations La María-Blanca de Jericó-5 and La María-Piartal-6.

Group 5 is divided into two: the first (group 7) Stem Diameter < 3.90 +/- 0.19 cm, Panicle Color: purple, green, others (7), Shape of Upper Leaves: rhomboid or triangular (3) for Porvenir-9, and the second (group 8) Stem Diameter > 3.90 +/- 0.19 cm, Panicle Color: purple (1), Shape of Upper Leaves: rhomboid (1) for Siachoque-2. Group 6 is divided: the first (group 9) Panicle Length < 27.17 +/- 2.55 cm, Growth Habit: branched up to the second third (3) for La María-Blanca de Jericó-5, and, the second (group 10) Panicle Length > 27.17 +/- 2.55 cm, Growth Habit: simple or branched up to the second third (5) for La María-Piartal-6.

Group 4 is subdivided into two groups: the first group (group 11) with Plant Height < 135.36 +/- 15.73 cm, Stem Color: purple, yellow or green (7), Upper Leaves Color: green (1), Shape of Upper Leaves: rhomboidal (1), Edge of Upper Leaves: dentate or serrated (6), or, entire, dentate or serrate (7), Presence of Teeth on Lower Leaves: absent or present (1) that characterize the populations Tuta-Blanca of Jericó-1 and Siachoque-Blanca of Jericó-8; the second group (group 12) with Plant Height > 135.36 +/- 15.73 cm, Stem Color: yellow (2), Upper Leaves Color: green-yellow (2), Upper Leaves Shape: triangular (2), Edge of Upper Leaves: entire or serrated (5), Presence of Teeth on Lower Leaves: absent (0) that characterize the Mongui-Piartal-4 and Sogamoso-Piartal-3 populations.

Group 9 is divided into: group 13 with Stem Diameter > 3.26 +/- 0.14 cm, Panicle Color: purple, green or others (7), Upper Leaf Edge: entire, toothed or serrated (7), Presence of Teeth on Upper leaves: absent or present (1) for Tuta-Blanca Jericó-1, and, group 14 with Stem Diameter < 3.26 +/- 0.14 cm, Panicle Color: purple or green (4), Edge of Upper Leaves: toothed or serrated (6), Presence of Teeth on Upper Leaves: present (2) for Siachoque-Blanca de Jericó-8. Group 12 is divided into: group 15 with Panicle

Length < 30.42 +/- 0.72 cm, Panicle Color: green (2) for Mongui-Piartal-4, and group 16 with Panicle Length > 30.42 +/- 0.72 cm, Panicle Color: purple or green (4) for Sogamoso-Piartal-3.

Considering the evaluation of the qualitative and quantitative descriptors, a dichotomous classification was proposed, which was useful for the definition of the groupings and of the morphotypes, for which it can be useful to select the phenotypic variants present in the different quinoa cultivars planted in the country.

1 If the plant has a panicle diameter of less than 21.87 cm, glomerulate panicle shape, intermedia or amarantiforme (7), color of upper leaves green or green-yellow (3), habit of simple or branched growth up to the lower third (4), color yellow streaks (2) ……..……..…….Combita-P-7

1´ If the plant has a panicle diameter greater than 21.87 cm, glomerulate panicle shape (1), color leaves green (1) or green-yellow (2), growth habit simple (1) and/or branched up to the second third (3), color green streaks (1)……:……group to 2

2 If the plant has the Edge of Upper Leaves notched (2) or serrated (3), Presence of Teeth on Upper leaves (2), Presence of Teeth on Lower leaves (2), pigmented axils absent (0) or present (1)……..……group to 3

2´ If the plant has entire or serrated (5), toothed or serrated (6) or entire Upper Leaf Edge, toothed or serrated (7), teeth on upper leaves absent or present (1), or present (2), teeth in lower leaves absent (0), or, absent or present (1), pigmented axils absent or present (1)…….group to 4

3 If the plant has Height less than 107.04 cm, Stem Diameter less than 4.44 cm, Diameter of Panicle less than 27.96 cm, Panicle Color purple (2), Shape of Upper Leaves rhomboid (1) or rhomboidal and triangular (3), edge of upper leaves notched (2), absence of pigmented axils (0), Simple Growth Habit (1)……group to 5

3´ If the plant has Height greater than 107.04 cm, Diameter of the Stem greater than 4.44 cm, Diameter of Panicle greater than 27.96 cm, Color of Panicle green (2), Shape Upper Leaves triangular (2), Edge Upper Leaves serrate (3), pigmented axils absent and/or present (1), Habit of Branched growth up to the second third (3), or, simple or branched up to the second third (5)…….group to 6

4 If the plant has Height less than 135.36 cm, Color Stem purple, yellow or green (7), Color Upper Leaves green (1), Shape Upper Leaves rhomboid (1), Edge Upper Leaves toothed or serrated (6) or whole, toothed or serrated (7), teeth on upper leaves absent or present (1) ……group to 7

4´ If the plant has a Height greater than 135.36 cm, Stem Color yellow (2), Color Upper Leaves green-yellow (2), Shape Upper Leaves triangular (2), Edge Upper Leaves entire or serrated (5), teeth on lower blades absent (0)…….……group to 8

5 If the plant has a Stem Diameter greater than 3.89 cm, Panicle Color purple (1), Leaf Shape Upper rhomboid (1) ……..……..……..Siachoque-P-2

5´ If the plant has a Stem Diameter of less than 3.89 cm, Panicle Color purple, green or others (7), Shape of upper leaves rhomboid or triangular (3) ……..…. ……..……..…..…..Porvenir-BJ-9

6 If the plant has a Panicle Length less than 27.16 cm, Growth Habit branched up to the second third (3) …….……..…….La Maria-BJ-5

6´ If the plant has a Panicle Length greater than 27.16 cm, Growth Habit Simple or branched until the second third (5)…….…..…..……La Maria-P-6

7 If the plant has a Stem Diameter greater than 3.25 cm, Panicle Color purple, green or others (7), Edge Upper Leaves entire, notched or serrated (7), teeth on upper leaves absent or present (1)…….……..…..Tuta-BJ-1

7´ If the plant has a Stem Diameter of less than 3.25 cm, Panicle Color purple or green (4), Border Upper leaves notched or serrated (6), teeth on upper leaves present (2).....…….……Siachoque-BJ-8

8 If the plant has Panicle Length less than 30.42 cm, Panicle Color green (2) ……..……Mongui-P-4

8´ If the plant has a Panicle Length greater than 30.42 cm, Panicle Color purple or green (4) ……..……..……Sogamoso-P-3

4. Discussion

In Colombia, quinoa is produced from cultivars that have not been previously identified or improved, which is why varietal mixtures are observed in all producing municipalities, with changes in morphology, physiology and phenology that depend on climatic conditions (Morillo et al., 2022b). Hence the importance of carrying out studies at an intrapopulation level that allow us to detect the best genetic variants in order to select them and thus produce varieties based on the identification of promising individuals present in the Blanca de Jericó and Piartal genotypes, which are the most cultivated in the department from Boyacá.

Internationally it is known that quinoa presents a high phenotypic variation which allows it to adapt to different agroclimatological conditions, for which these differences can be considered as an adaptive and survival response to extreme environmental conditions (Valverde-Ramos et al., 2022). The analyzes of the qualitative characteristics showed that those associated with the panicle were the most diverse. Results similar to those obtained in studies of morphoagronomic characterization of the germplasm both internationally and nationally (Afiah et al., 2018). Alanoca and Machaca (2017) found that the expression of these characteristics is affected by the morphological changes of quinoa during its maturation.

Traits such as number, density, and shape panicle may be valuable for genetic introgression in quinoa breeding

programs, because these traits show high heritability and are directly correlated with yield components. (Al-Naggar et al., 2017) and have great agronomic importance for quinoa producers in the country (Manjarres et al., 2021a, b).

Plant height was within the ranges found in other quinoa characterization studies in Colombia (Morillo et al., 2020). Panicle lengths between 22 and 40 cm have been reported (López et al., 2012) and in this study panicles between 12 and 46 cm were found. The length of the panicles in quinoa plants depends on the growth and differentiation processes that occur in the apical meristem (Garcia-Parra et al., 2019).

Studies also show a strong correlation between panicle diameter and yield (Hussain et al., 2020); the diameters in this study were between 8 and 39 cm, results similar to those found by Manjarres et al. (2021b), where a high diversity is reported at the interindividual level, mainly in the length, diameter, and color of the panicle.

Manjarres et al. (2021a) reported that although qualitative variables constitute a fundamental tool to determine the adaptation strategies of plants and are used as varietal descriptors (Katwal and Bazile, 2020), in their study these traits presented a wide genetic variability, as shown shows in the different colorations of the striae, axils, panicles and seeds This behavior was also observed in quinoa materials evaluated in the Rio Grande do Sul region of Brazil (Vergara et al., 2020) and in cultivars of Quinoa Blanca de Jericó, expressed in different pigmentations within individuals in structures such as panicles and stems.

The results found in the quantitative variables were similar to those reported in other studies of genetic diversity in quinoa (Afiah et al., 2018; Infante et al., 2018). The results found in the quantitative variables were similar to those reported in other studies of genetic diversity in quinoa. Tukey's test ($p \leq 0.05$) showed differences between and within the evaluated morphotypes for all quantitative variables, especially those associated with yield, results similar to those found in morphoagronomic characterization studies in Boyacá (Morillo et al., 2020; Manjarres et al., 2021 a, b; Morillo et al., 2022b).

The results showed a significant correlation between AP and DT for all populations, as was also observed by Madrid et al. (2018) in the evaluation of morphological characteristics related to the improvement of quinoa yield. LP and DP were positively associated with AP, thus showing that taller individuals develop longer panicles, as found by Farooq et al. (2018) and Morillo et al. (2020). Correlation studies are an important step in quinoa improvement programs since the information that is obtained is useful for estimating the correlated response to selection for the formulation of selection indices (Afiah et al., 2018; Al-Naggar et al., 2018).

The Cluster Analysis showed that the individuals of the Piartal and Blanca de Jericó quinoa were grouped mainly by morphological characteristics associated with plant height, panicle length, pigmented axillae, and leaf characteristics, as reported by Morillo et al. (2020); the clusters showed a lax distribution of the individuals with an association of the characteristics presence or absence of striae, growth habit, color, shape, length and diameter of the panicle, results that were consistent with morphological characterization studies on quinoa (Curti et al., 2014; Infante et al., 2018; Farooq et al., 2018).

The morphoagronomic characterization of Blanca de Jericó and Piartal quinoa genotypes in the six evaluated municipalities showed high intrapopulation phenotypic variability that depended on the agroclimatological conditions of each site (Infante et al., 2018; Morillo et al., 2020), mainly as the result of the fact that quinoa is a rustic crop with a broad agroecological adaptation that can tolerate different types of stress and that is a food security crop for the Andean community since with farmers who have maintained and selected seeds for generations (Alvarez-Flores et al., 2018).

However, the presence of morphotypes in quinoa crops is not a desirable condition since it means that there are still no pure materials or local varieties but only materials in the process of domestication, which is a limitation for the implementation of cultivation technologies. Therefore, a dichotomous classification is proposed to facilitate the selection of morphotypes in the field.

The morphoagronomic evaluation of the intraspecific variation of the Blanca de Jericó and Piartal quinoa genotypes in the Department of Boyacá showed a wide segregation of the phenotypic characteristics especially related to the color of different plant structures. This variation that occurs at the interindividual level in farmers' fields, in the materials that they plant and select cycle after cycle is not desirable, since it reduces the quality and profitability of the crop, and also suggests selection and purification processes efficient that lead to obtaining "pure" cultivars with better yields and adapted to local conditions.

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