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ORIGINAL RESEARCH ARTICLE

The phenotypic feature of arracacha (*Arracacia xanthorrhiza* Bancroft.) of three regional cultivars in Tolima, Colombia

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ABSTRACT

The *xanthorrhiza* species of the genus *Arracacia* belongs to the Apiaceae family and is known for its ability to generate tuberous reservoir roots that are harvested annually and marketed fresh in South American countries such as Colombia, Brazil, Venezuela, Peru, Bolivia and Ecuador. In Colombia, arracacha is planted mainly in 15 departments and the regional cultivars are differentiated by the color of the leaves, petiole and tuberous root, the best known being *amarilla común* or *paliverde*, *yema de huevo*, and *cartagenera*. There are studies that have characterized regional materials by applying a limited number of descriptors, but they do not allow knowing the morphology and phenotypic differentiation of each one; therefore, their definition and characterization constitute a support in breeding programs that allow the efficient use of the genetic potential and increase the knowledge about the diversity of cultivars. Phenotypic characterization and description of three cultivars was performed during two production cycles (2016 and 2018) in two phases (vegetative and productive) applying 74 morphological variables (42 qualitative and 32 quantitative) organized in seven groups of variables: plant, leaf, leaflet, petiole, propagule, stock and tuberous root. A factorial analysis for mixed data (FAMD) was performed, which incorporated a multivariate analysis with all variables and identified 11 discriminant variables, 8 qualitative and 3 quantitative, which can be used in processes of characterization of arracacha materials. A morphological description of each cultivar was made, which means that this is the first complete characterization study of regional arracacha materials in Colombia.

Keywords: Tuberous Root; Genetic Material; Trait; Variable

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1. Introduction

The Andean region preserves a large part of the genetic resources of nutritional and economic importance to the world; among them, tubers and tuberous roots, which are the main source of nutrition for farmers with limited resources because they provide energy to their bodies and production does not generate high costs[1]. Arracacha (*Arracacia xanthorrhiza* Bancroft.) is a tuberous root, native to the Andes and whose domestication occurred centuries ago, possibly before the potato[2]. It is perennial, but is cultivated as an annual to take advantage of the root crop which is the commercial and most morphologically variable organ[3,4].

Arracacha adds texture and flavor to dishes, has potential for agroindustry and nutritionally provides calories, fiber and minerals such as calcium, phosphorus, magnesium and iron[5]. However, it is a little

researched species. It is important in countries such as Brazil, where it is an ingredient present in haute cuisine; in Bolivia and Peru it remains a food of isolated communities with little presence in markets, and in Colombia its cultivation is not considered a priority in national or departmental agricultural development plans[2,6].

The crop is found from Venezuela to Bolivia, with the largest planting area in Brazil, Colombia, Ecuador and Peru; it has a smaller scale of production in northeastern Argentina, Costa Rica, Puerto Rico, Dominican Republic and Haiti[2]. According to Garnica *et al.*[7], the main producer of arracacha in the world is Brazil with 8,168 ha sown and a production of 109,217 t, followed by Colombia with 8,037 ha and 74,586 t. At the national level, the municipality of Cajamarca in the department of Tolima concentrates for 51.79% of the national production with 5,000 ha and 60,000 t[8].

In Colombia, specifically in the Sibundoy valley (Putumayo), there is a great variety of unique genotypes of *A. xanthorrhiza* and *Neonelsonia acuminata* Benth. known as "wild arracacha", which supports the hypothesis of the south of the country as a center of dispersion and part of the center of primary diversity of the genus. The crop has been conserved by different ethnic groups and indigenous communities throughout the country for sale or self-consumption. Planting is mainly linked to the tradition acquired from ancestors, as it was considered a micro and smallholder crop[6,9]. However, its sowing has been potentiated and it is now a productive system of small, medium and large producers who grow it for fresh marketing.

Arracacha cultivars are differentiated by leaf color, petiole color, shape and color of the tuberous root. Alvarado and Ochoa[6] reported the cultivars paliverde, palirrusia, palinegra and yema de huevo as the most widely planted and consumed in the municipality of Boyacá, and sata and sata morada in the municipality of Gachantivá (department of Boyacá). Subsequently, Alvarado *et al.*[9] identified in Boyacá nine cultivars classified into two groups, *De cepa o tarro* where yucatana, amarilla de tarro and blanca de tarro, sata and sata morada cultivated in the region since the 1950s are located; *De Apio*, which includes paliverde, palirrusia, palinegra and *yema de huevo*, introduced to the region by workers who migrated from Cajamarca (Tolima). Atencio *et al.*[3] reported the cultivars *amarilla común*, *yema de huevo* and *cartagenera* as the major cultivars planted in the municipality of Cajamarca (Tolima).

According to the results of participatory research in the area with the largest arracacha planting area, the most propagated cultivar is known as *como amarilla común* or *paliverde*, which occupies about 95% of the national planting; followed by *yema de huevo*, a genotype that was highly planted during 2009 and 2010, but its productive potential declined rapidly, which led to a significant decrease in planting areas; and in third place is *cartagenera*, which was displaced over the years because of its susceptibility to pests and diseases.

Identifying and knowing the phenotypic characteristics of regional arracacha cultivars allows differentiating them from each other, which is important to avoid mixing vegetative seed in the field, a fact that directly affects the harvest since the price is punished for lack of uniformity and quality in the commercial roots. In addition, a crop with a diversity of genetic materials within the same lot makes agronomic management difficult, since nutritional requirements, phytosanitary management, weed control and postharvest are specific to each genotype. Therefore, the definition of descriptors and phenotypic characterization constitute a support in breeding programs that allow the efficient use of genetic potential and broaden knowledge about cultivar diversity.

The objective of this work was to phenotypically characterize three regional cultivars of arracacha in the department of Tolima, Colombia, known as *como amarilla común*, *yema de huevo* and *cartagenera*, by means of 74 qualitative and quantitative morphological characters organized in seven groups of variables: plant, leaf, leaflet, petiole, petiole, propagule, stock and tuberous root, as well as to determine the existing phenotypic relationship. This study is the first complete phenotypic characterization that applies the largest number of descriptors for *Arracacia xanthorrhiza* Bancr. in Colombia.

2. Materials and methods

2.1 Location

The study was developed in two productive cycles of the crop during 2016 and 2018, in the municipality of Cajamarca (Tolima) in the village of La Leona, located at 2040 m s. n. m., with geographical coordinates 4°23′27.3″ N and 75°30′75.3″ W. The life zone corresponds to very humid premontane forest (bh-P) and humid low montane forest (bh-MB) with an undulating and broken relief with soils derived from volcanic ash, deep, good permeability and sandy-loam texture. The temperature recorded was maximum 28.7 °C, minimum 8.6 °C and average 18.7 °C, with average relative humidity of 81.9% and annual precipitation of 777.8 mm/year, with bimodal distribution[7].

2.2 Plant material

Twenty *A. xanthorrhiza* plants were evaluated for each regional cultivar, *amarilla común, yema de huevo* and *cartagenera*. Asexual seed collected from 12-month-old mother plants was sown during the two production cycles. The seed was cut with 5 cm of petiole and 2 rings of stock, previously disinfected with 5% sodium hypochlorite for 10 seconds[3].

2.3 Agronomic management

This was done uniformly for all treatments. It included soil preparation, manual and chemical control of weeds and implementation of a fertilization plan based on the recommendations of Souza and Madeira[10], who report the following nutritional requirements: N 2.09; P 0.77; K 5.29; Ca 0.25; Mg 0.19 and S 0.29 kg ha^{-1} for the production of 1 t ha^{-1} of fresh commercial roots. In nutrient extraction, the following decreasing order was observed: K > N > P > S > Ca > Mg for macro and Fe > Mn > Zn > B > Cu > Mo for micronutrients. Pests and diseases were controlled according to their incidence and level of damage to the plants.

2.4 Experimental design

A completely randomized design was established with four replications and three treatments represented by the cultivars *amarilla común*, *yema de huevo* and *cartagenera*. Soil preparation was done by forming mounds with a planting distance between plants of 0.5 m and 1.2 m between rows with a population density equivalent to 16,666 plants ha^{-1}. Each experimental unit with an area of 25 m^2 consisted of 50 plants. The following were taken five plants located in the central furrow of each experimental unit, avoiding the edge effect. The total area of the experiment was 300 m^2 with a slope percentage of 15% and a flat to slightly undulating relief.

2.5 Morphological variables

In each production cycle the cultivars were evaluated in two phases: phase I, carried out at 8 months of age, consisted of the evaluation of the vegetative vigor of the plants, and phase II, during the harvest at 12 months, the characters corresponding to the production of tuberous roots were recorded.

A total of 74 morphological, agronomic and yield characters were evaluated, including characters from descriptors developed by CIP in 2004 (unpublished), Rosso *et al.*[11], Seminario[12] and Garnica *et al.*[13]. Forty-two qualitative and 32 quantitative variables were included, organized following the structure of Garnica *et al.*[13] with some modifications. According to the structure and/or formation of the plant, abbreviations were defined that grouped the variables as follows: plant: P, leaf: HJ, leaflet: FOL, petiole: PE, stock: CP, propagule: PR and tuberous root: RT.

In commercial crops, multiplication is clonal, since the vegetative seed known as propagule, shoot, seed or sprout is subdivided into two classes: propagules that reach physiological maturity (suitable for planting) and the offspring that are smaller and have a crescent-shaped base (without viability). The tuberous root is subdivided into: commercial with length ≥8 cm and diameter ≥3 cm and non-commercial with smaller size[14]. The qualitative variables of pigmentation of the structures were identified using the Munsell *Plant Tissue* color book.

Table 1. Variables evaluated to characterize three cultivars of arracacha in Cajamarca, Tolima, Colombia (2016 and 2018)

Structure and/or training	Code	Variables	Categories or unit of measurement
Plant: P	1_P_ALTcm	Height	Quantitative (cm)
	2_P_CANcm	Plant diameter	Quantitative (cm)
	3_P_PESkg	Total weight of complete plant	Quantitative (kg)
	4_P_AERkg	Total weight of aerial part (leaflet + petiole)	Quantitative (kg)
	33_P_HC	Growth habit	1. Straight 2. Intermediate 3. Prostrate
	34_P_PT	Plant size	1. Low 2. Medium High
	35_P_CON	Conformation of the plant	1. Lax 2. Intermediate 3. Compact
Leaf: HJ	5_HJ_PESkg	Total leaf weight	Quantitative (kg)
	6_HJ_LGcm	Flag leaf length	Quantitative (cm)
	7_HJ_ANcm	Blade width	Quantitative (cm)
	36_HJ_CFOLL	Predominant color of foliage	1. Yellow green 2. Green 3. Dark green 4. Purple green 5. Grayish purple with green
	37_HJ_CENV	Predominant color of underside	1. Yellow olive green 2. Yellow green 3. Olive green 4. Light olive green 5. Olive green with pigmented veins 6. Olive green with pigmented veins and edges
	38_HJ_CENV*	Predominant color of underside	Book Munsell Plant Tissue
	39_HJ_CSENV	Secondary color of underside	0. Absent 1. Wine red 2. Grayish purplish red
	40_HJ_CSENV*	Secondary color of underside	Book Munsell Plant Tissue
	41_HJ_DSENV	Secondary color distribution of underside	0. Absent 1. Border 2. Ribs 3. Border and ribs 4. Irregularly distributed 5. Ribbed edge and lamina
	42_HJ_CHAZ	Predominant beam color	Light olive green 2. Olive green 3. Dark olive green 4. Deep red 5. Purple 6. Dark green with red veins
	43_HJ_CHAZ*	Predominant beam color	Book Munsell Plant Tissue
	44_HJ_CSHAZ	Secondary beam color	0. Absent 1. Light green 2. Dark green 3. Intense red 4. Purple 5. Dark green with red veins
	45_HJ_CSHAZ*	Secondary beam color	Book Munsell Plant Tissue
	46_HJ_ DCSHAZ	Secondary beam color distribution	0. Absent 1. Border 2. Ribs 3. Border and ribs 4. Irregularly distributed
Leaflet: FOL	47_FOL_CB	Leaflet edge color	0. Absent 1. Grayish orange 2. Reddish purple 3. Grayish purple
	48_FOL_CB*	Leaflet edge color	Book Munsell Plant Tissue
	49_FOL_B	Leaflet edge	1. Slightly incised and biserrated 2. Medium incised 3. Deeply incised
	50_FOL_AC	Terminal leaflet acumen	0. Absent 1. Slightly acuminate 2. Accumulated 3. Extensively acuminate
	51_FOL_DIS	Dissection of the terminal leaflet	1. Low 2. Medium 3. High
Petiole: PE	8_PE_PESkg	Total weight of petiole	Quantitative (kg)
	9_PE_N	Number of petioles	Quantitative (unit)
	10_PE_LGcm	Petiole length	Quantitative (cm)
	52_PE_C	Predominant color of petiole	Olive green 2. Yellow green 3. Dark yellow green 4. Strong olive green 5. Green with reddish purple lower third 6. Green with grayish purple upper part 7. Green with grayish purple upper third 8. Purple red 9. Purplish brown
	53_PE_C*	Predominant color of petiole	Book Munsell Plant Tissue
	54_PE_SC	Secondary color of petiole	0. Absent 1. Pale yellow green 2. Yellow green 3. Reddish purple 4. Grayish purple 5. Purple in the middle
	55_PE_STR	Petiole striae	0. Absent 1. Present
	56_PE_CER	Serosity of petiole	0. Absent 1. Present

Table 1. (*Continued*)

Structure and/or training	Code	Variables	Categories or unit of measurement
Propagule: PR	11_PR_N	Number of propagules	Quantitative (unit)
	12_PR_PESkg	Total weight of propagules	Quantitative (kg)
	13_PR_PPESg	Average propagule weight	Quantitative (g)
	14_PR_ANcm	Propagule width	Quantitative (cm)
	15_PR_LGcm	Length of propagules	Quantitative (cm)
	16_PR_NHI	Number of tillers	Quantitative (unit)
	17_PR_PESHIg	Total weight of tillers	Quantitative (g)
	57_PR_C	External color of propagule	1. White green 2. Yellow green 3. Dark yellow green 4. Purple red 5. Dark purple 6. Grayish purple 7. Purple 8. Purple red and white green
	58_PR_C*	External color of propagule	Book Munsell Plant Tissue
	59_PR_CB	Propagule base color	1. White 2. Light reddish purple 3. Dark reddish purple 4. Purple gray 5. Light pink
	60_PR_CB*	Propagule base color	Book Munsell Plant Tissue
	61_PR_CP	Predominant color of propagule pulp	1. White 2. Yellow 3. Dark yellow 4. Pale yellow or cream 5. Orange 6. Light purple
	62_PR_CP*	Predominant color of propagule pulp	Book Munsell Plant Tissue
	63_PR_CSP	Secondary color of propagule pulp	0. Absent 1. Yellowish orange 2. Grayish purple 3. Purple
	64_PR_DCSP	Secondary propagule color distribution	0. Absent 1. Cortical ring 2. Cortical ring and several rings at the base of the hill
Stock: CP	18_CP_PESkg	Total weight of the stock	Quantitative (kg)
	19_CP_LHcm	Horizontal length of the stock	Quantitative (cm)
	20_CP_LVcm	Vertical length of the stock	Quantitative (cm)
Tuberous root: RT	21_RR_N	Number of reservoir roots	Quantitative (unit)
	22_RR_PESkg	Total weight of reservoir roots	Quantitative (kg)
	23_RR_NC	Number of commercial reservoir roots	Quantitative (unit)
	24_RR_PESCkg	Total weight of commercial reservoir roots	Quantitative (kg)
	25_RR_PPESCg	Average weight of commercial reservoir roots	Quantitative (g)
	26_RR_ANCcm	Average width of commercial reservoir roots	Quantitative (cm)
	27_RR_LGCcm	Average length of commercial reservoir roots	Quantitative (cm)
	28_RR_NNC	Number of non-commercial reservoir roots	Quantitative (unit)
	29_RR_ PESNCkg	Total weight of non-commercial reservoir roots	Quantitative (kg)
	30_RR_ PPESNCg	Average weight of commercial non-reservoir roots	Quantitative (g)
	31_RR_ ANNCcm	Average width of commercial non-reservoir roots	Quantitative (cm)
	32_RR_ LGNCcm	Average length of commercial non-reservoir roots	Quantitative (cm)
	65_RR_COL	Predominant color of the reservoir root surface	1. White 2. Light yellow 3. Yellow 4. Dark yellow 5. Orange 6. Light reddish purple 7. Purple
	66_RR_COL*	Predominant color of the reservoir root surface	Book Munsell Plant Tissue
	67_RR_COLS	Secondary color of the reservoir root surface	0. Absent 1. Reddish purple 2. Grayish purple

Table 1. *(Continued).*

Structure and/or training	Code	Variables	Categories or unit of measurement
Tuberous root: RT	68_RR_DCOLS	Secondary color distribution of the reservoir root	0. Absent 1. Only in vascular ring 2. Vascular ring and cortical zone 3. Regularly distributed 4. Equally distributed
	69_RR_F	Reservoir root shape	Ovoid 2. Conical 3. Fusiform 4. Regular 5. Irregular
	70_RR_COLP	Predominant color of reservoir root pulp	White (1), Light yellow (2), Yellow (3), Dark yellow (4), Yellowish orange (5), Violet (6)
	71_RR_COLP*	Predominant color of reservoir root pulp	Book Munsell Plant Tissue
	72_RR_COLSP	Secondary color reservoir root pulp	0. Absent 1. Dark yellow 2. Reddish purple 3. Grayish purple
	73_RR_COLSP*	Secondary color reservoir root pulp	Book Munsell Plant Tissue
	74_RR_DCOLSP	Reservoir root pulp color distribution	1. Cortical (vascular) ring 2. Irregularly distributed 3. Vascular ring and medulla 4. Everything except the medulla

* The code corresponding to the Munsell Plant Tissue color chart is recorded.

The distribution of morphological attributes was organized based on the number of variables according to the following scheme (qualitative, quantitative) for each organ: plant-P (3;4), leaf-HJ (11;3), leaflet-FOL (5;0), petiole-PE (5;3), propagule-PR (8;7), CP-stock (0;3), and tuberous root-RT (10;12). The variables are shown in **Table 1**.

2.6 Statistical analysis

The data were subjected to an initial exploratory and descriptive analysis to determine and discard outliers. For quantitative variables, box and whisker plots were reviewed to determine outliers above three standard deviations. Two types of analysis were performed, one univariate and the other multivariate. The univariate analysis differed between qualitative and quantitative variables. For qualitative variables, data were considered for the 20 plants evaluated for each cultivar and a distribution of relative frequencies was made, obtaining percentages for each category within the cultivar. For quantitative variables, analysis of variance was performed to compare between cultivars. In those variables where there were statistical differences ($p < 0.05$), a Tukey mean test was performed between cultivars at 5% significance. These analyses were carried out using the *multcomp* package R version 3.6.3[15,16].

For multivariate analysis, each plant evaluated represented an operational taxonomic unit (OTU). A factor analysis for mixed data (AFMD) was performed with the 74 variables. This allows the analysis of the similarity between individuals, and also combines the techniques of principal component analysis (PCA) and multiple correspondence analysis (MCA), widely used in studies of genetic variability[17,18]. Then, the accumulated variability in the first two dimensions was projected by means of an OTU factor map and the relationship of the OTU for the three cultivars was identified. Subsequently, the variables with the highest cosine squared to dimension one and two were selected, determining these as discriminants in differentiating the cultivars evaluated. The analyses were performed with R software version 3.6.3[16], using the *FactoMineR* and *factoextra* packages in the calculation of the AFMD results[19,20].

3. Results and discussion

3.1 Analysis of set characteristics: Qualitative and quantitative

Among the 74 morphological characters evaluated in the three arracacha cultivars, in 13 qualitative variables there was no variability (**Table 2**) and in five of the quantitative characters there were no significant differences (**Table 3**), corresponding to 17.56% and 6.7% respectively. In 29 qualitative traits there was variation among the plants evaluated (**Table 4**) and 27 quantitative variables showed significant statistical differences ($p \leq 0.05$) among cultivars (**Table 5**). Blas *et al.*[21] used 20 plants for the characterization of 3 species of arracacha in Peru, using 100 morphological characters (56 qualitative and 44 quantitative). Multivariate analyses al-

Table 2. Unvariable qualitative morphological variables in three arracacha cultivars in Cajamarca, Tolima, Colombia

Code	Variable	Result
33_P_HC	Growth habit	1. Erecto
50_FOL_AC	Terminal leaflet acumen	2. Accumulated
51_FOL_DIS	Dissection of the terminal leaflet	2. Medium
54_PE_SC	Secondary color of petiole	0. Absent
55_PE_STR	Petiole striae	1. Present
56_PE_CER	Serosity of petiole	0. Absent
62_PR_CP*	Predominant color of propagule pulp	5Y 8/6
63_PR_CSP	Secondary color of propagule pulp	0. Absent
64_PR_DCSP	Secondary propagule color distribution	0. Absent
65_RT_COL	Predominant color of the tuberous root surface	3. Yellow
67_RT_COLS	Secondary color of the tuberous root surface	0. Absent
68_RT_DCOLS	Secondary color distribution of the tuberous root	0. Absent
69_RT_F	Tuberous root shape	2. Conical

Table 3. Quantitative morphological variables without significant differences in three cultivars of arracacha in Cajamarca, Tolima, Colombia

Code	Variable	Common yellow	Cartagenera	Egg yolk
6_HJ_LGcm	Flag blade length (cm)	22.70 ± 1.04 a	24.40 ± 0.95 a	22.30 ± 0.64 a
11_PR_N	Number of propagules (unit)	17.00 ± 0.89 a	13.40 ± 1.31 a	16.70 ± 1.19 a
20_CP_Wcm	Vertical length of stock (cm)	13.80 ± 0.69 a	12.70 ± 0.53 a	14.00 ± 0.57 a
21_RR_N	Number of tuberous roots (unit)	10.70 ± 0.76 a	8.45 ± 0.65 a	9.40 ± 0.99 a
32_RR_LGNCcm	Average length of commercial non-tuberous roots (cm)	7.64 ± 0.40 a	6.83 ± 0.32 a	7.52 ± 0.61 a

The data presented correspond to the average of four replications. Different letters indicate significant statistical differences ($p \leq 0.05$) according to the Tukey test. The numbers after the symbol ± indicate the standard error.

Table 4. Qualitative variables to characterize three cultivars of arracacha in Cajamarca, Tolima, Colombia (2016 and 2018)

Variable code	Category	*Amarilla común* (%)	*Cartagenera* (%)	*Yema de huevo* (%)	Chi-square X^{2*}	Variable code	Category	*Amarilla común* (%)	*Cartagenera* (%)	*Yema de huevo* (%)	Chi-square X^{2*}
34_P_PT	1. Bass	0	100	100	60	53_PE_C*	5GY 6/8	5	0	20	
	2. Medium	100	0	0			5GY 7/6	10	0	0	
35_P_CON	1. Lax	0	35	0	42.81		5GY 7/8	30	0	45	
	2. Inter	15	65	75			5R 3/2	0	30	0	
	3. Comp	85	0	25			5R 3/4	0	70	0	
36_HJ_CFOLL	1. VdeAma	0	0	100	96	57_PR_C	2. VdeAma	25	0	0	68.57
	2. Vde	75	0	0			4. RojP	75	0	100	
	3. VdeOsc	25	100	0		58_PR_C*	5. PurpO	0	100	0	114.9
37_HJ_CENV	1. VdeOlv	75	0	85	60.93		2.5GY 6/6	25	0	0	
	4. VdeOlvc	25	0	15			2.5R 4/4	0	5	0	
	5. VdeOlvNP	0	100	0			2.5R 4/6	0	5	0	
38_HJ_CENV*	5GY 4/4	20	60	10	31.94		5R 3/4	45	0	0	
	5GY 4/6	0	15	0			5RP 3/6	0	50	0	
	5GY 4/8	5	0	0			5RP 3/8	0	40	0	
	5GY 5/4	25	25	15			5RP 4/10	30	0	5	
	5GY 5/6	50	0	75			5RP 4/8	0	0	95	

Table 4. (*Continued*)

Variable code	Category	*Amarilla común* (%)	*Cartagenera* (%)	*Yema de huevo* (%)	Chi-square X^{2}*	Variable code	Category	*Amarilla común* (%)	*Cartagenera* (%)	*Yema de huevo* (%)	Chi-square X^{2} *
39_HJ_CSENV	0. Aus	100	0	100	60	59_PR_CB	2. PurpRC	0	0	100	120
	1. Rjov	0	100	0			3. PurpRO	100	0	0	
40_HJ_CSENV*	0. Aus	100	0	100	60		4. PurpG	0	100	0	
	5RP 3/4	0	100	0		60_PR_CB*	2.5R 4/6	0	90	0	120
41_HJ_DSENV	0. Aus	100	0	100	60		5RP 3/10	35	0	0	
	2. Nerv	0	100	0			5RP 3/2	0	10	0	
42_HJ_CHAZ	1. VdeCl	100	0	0	120		5RP 3/6	5	0	0	
	3. VdeOsc	0	0	100			5RP 3/8	60	0	0	
	6. VdeOscNR	0	100	0			5RP 4/8	0	0	100	
43_HJ_CHAZ*	5GY 3/4	95	100	0	57.54	61_PR_CP	2. Amall	100	0	0	
	5GY 4/4	5	0	10			3. AmallO	0	0	100	
	5GY 4/6	0	0	90			4. AmallC	95	100	100	
44_HJ_CSHAZ	0. Aus	100	0	100	60		5. Crem	0	100	0	
	2. VdeOscNR	0	100	0		66_RT_COL*	5RP 4/6	5	0	0	52.87
45_HJ_CSHAZ*	0. Aus	100	0	100	60		5Y 6/6	5	0	0	
	10R 3/4	0	70	0			5Y 8/2	0	80	0	
	10R 4/4	0	20	0			5Y 8/4	30	20	15	
	2.5R 4/6	0	10	0			5Y 8/6	60	0	85	
46_HJ_DCSHAZ	0. Aus	100	0	100	60	70_RT_COLP	2. AmallC	100	100	0	60
	3. BdNerv	0	100	0			3. Amall	0	0	100	
47_FOL_CB	0. Aus	100	0	100	60	71_RT_COLP*	5Y 6/6	20	0	0	67.55
	3. PurpG	0	100	0			5Y 8/2	0	70	0	
48_FOL_CB*	0. Aus	100	0	100	60		5Y 8/4	10	30	0	
	2.5R 3/4	0	45	0			5Y 8/6	70	0	75	
	2.5R 4/6	0	25	0			5Y 8/8	0	0	25	
	2.5YR 3/4	0	30	0		72_RT_COLSP	0. Aus	85	100	0	64.86
49_FOL_B	1. LiginB	100	0	0	92.3		3. PurpR	15	0	0	
	Medin	0	100	30			4. NaAmall	0	0	100	
	3. Profin	0	0	70		73_RT_COLSP*	0. Aus	85	100	0	64.86
52_PE_C	2. VdeAma	100	0	100	10		2.5Y 8/6	0	0	65	
	8. RojP	0	100	0			2.5Y 8/8	0	0	35	
53_PE_C*	2.5GY 6/8	15	0	5	73.85		5RP 3/4	15	0	0	
	2.5GY 7/8	10	0	5		74_RT_DCOLSP	0. Aus	85	100	0	64.86
	5GR 7/8	5	0	0			1. AnillVM	0	0	100	
	5GY 5/6	10	0	0			2. IrregD	15	0	0	
	5GY 6/6	15	0	25							

* All variables had a p-value <0.01.

Table 5. Quantitative variables to characterize three cultivars of arracacha in Cajamarca, Tolima, Colombia (2016 and 2018)

Variable code	Common yellow	Cartagenera	Egg yolk
1_P_ALTcm	65.80 ± 2.37 b	51.30 ± 1.85 a	55.90 ± 1.94 a
2_P_ANCcm	112.42 ± 1.92 b	89.71 ± 4.23 a	97.15 ± 2.79 a
3_P_PESkg	4.95 ± 0.28 c	2.20 ± 0.16 a	3.83 ± 0.38 b
4_P_AERkg	0.96 ± 0.10 b	0.30 ± 0.03 a	0.44 ± 0.04 a
5_HJ_PESkg	0.46 ± 0.04 b	0.15 ± 0.01 a	0.24 ± 0.02 a
7_HJ_ANcm	26.10 ± 1.47 b	22.40 ± 0.97 a	22.70 ± 0.90 a
8_PE_PESkg	0.49 ± 0.06 b	0.13 ± 0.01 a	0.19 ± 0.02 a
9_PE_N	83.00 ± 4.87 c	35.00 ± 2.78 a	50.40 ± 2.03 b
10_PE_LGcm	32.60 ± 1.35 b	25.60 ± 1.39 a	25.50 ± 1.39 a
12_PR_PESkg	0.38 ± 0.03 b	0.17 ± 0.01 a	0.21 ± 0.01 a
13_PR_PPESg	22.20 ± 1.63 b	13.00 ± 0.69 a	13.10 ± 0.69 a
14_PR_ANcm	3.06 ± 0.07 b	2.54 ± 0.03 a	2.57 ± 0.03 a
15_PR_LGcm	7.49 ± 0.19 b	6.78 ± 0.14 a	6.43 ± 0.12 a
16_PR_NHI	14.75 ± 1.57 b	8.35 ± 1.02 a	7.60 ± 1.17 a
17_PR_PESHIg	155.90 ± 23.99 b	52.20 ± 7.72 a	51.60 ± 10.39 a
18_CP_PESkg	1.27 ± 0.08 b	0.76 ± 0.06 a	1.14 ± 0.11 b
19_CP_LHcm	21.10 ± 0.90 ab	18.60 ± 0.64 a	21.50 ± 0.86 b
22_RR_PESkg	1.90 ± 0.15 b	0.66 ± 0.07 a	1.81 ± 0.26 b
23_RR_NC	6.40 ± 0.39 b	4.25 ± 0.36 a	7.30 ± 0.92 b
24_RR_PESCkg	1.71 ± 0.17 b	0.55 ± 0.06 a	1.77 ± 0.26 b
25_RR_PPESCg	269.00 ± 19.76 b	128.00 ± 10.14 a	235.00 ± 23.93 b
26_RR_ANCcm	5.57 ± 0.14 c	4.33 ± 0.15 a	4.90 ± 0.15 b
27_RR_LGCcm	15.20 ± 0.52 b	12.20 ± 0.36 a	16.00 ± 0.62 b
28_RR_NNC	4.30 ± 0.67 b	4.20 ± 0.60 b	2.10 ± 0.40 a
29_RR_PESNCkg	0.18 ± 0.03 b	0.10 ± 0.01 a	0.05 ± 0.09 a
30_RR_PPESNCg	36.60 ± 3.04 b	22.90 ± 1.90 a	18.20 ± 2.38 a
31_RR_ANNCcm	2.95 ± 0.13 b	2.42 ± 0.10 b	2.14 ± 0.08 a

The data presented correspond to the average of four replications. Different letters indicate significant statistical differences ($p \leq 0.05$) according to the Tukey test. The number after the ± symbol indicate the standard error.

lowed differentiation of *Arracacia* species using 28 morphological characters identified as discriminant (17 qualitative and 11 quantitative). Pinto-Acero *et al.*[22] characterized arracacha yema huevo, paliverde and yucatana materials in the department of Boyacá, using 3 quantitative morphoagronomic variables and 7 color variables using the CIELab coordinate system.

The results of the AFMD showed that 10 dimensions grouped 71.6% of the variability. This value is higher than that found by Garnica *et al.*[13], who characterized 96 accessions of the germplasm bank of Colombia and found a percentage of variability of 55% in the first 10 components and reported that the high values of variability allow defining quantitative and qualitative characters for the morphological characterization of cultivars.

Figure 1 shows the formation of 3 groups for the 60 plants evaluated, dimension 1 accounted for 26.5% and dimension 2 for 15.8%. In the red centroid were grouped the individuals corresponding to the *amarilla común* cultivar, in the blue centroid the individuals corresponding to the *yema de huevo* cultivar and in the green centroid individuals corresponding to the *cartagenera* cultivar. The AFMD showed 20 variables (15 qualitative and 5 quantitative) as discriminant characters for the 3 cultivars (intercultivar differentiation) represented in **Table 6**,

which correspond to the characters with discrimi- nant power for genetic diversity.

Table 6. Cosine squared of the most representative variables in dimension 1 and 2 for *amarilla común*, *cartagenera* and *yema de huevo* cultivars

Code	Variables	Dim 1	Dim 2
36_HJ_CFOLL	Predominant color of foliage	0.6918*	0.8983
37_HJ_CENV	Predominant color of underside	0.9369	0.0451
39_HJ_CSENV	Secondary color of underside	0.9364	0.0226
41_HJ_DSENV	Secondary color distribution of underside	0.9364	0.0226
42_HJ_CHAZ	Predominant beam color	0.9497	0.9291
45_HJ_CSHAZ	Secondary beam color	0.9364	0.0233
46_HJ_DCSHAZ	Secondary beam color distribution	0.9364	0.0226
48_FOL_CB	Leaflet edge color	0.9380	0.0234
53_PE_C	Predominant color of petiole	0.9505	0.2769
58_PENV_C	External color of propagule	0.9530	0.8491
60_PENV_CB	Propagule base color	0.9507	0.9331
61_PR_CP	Predominant color of propagule pulp	0.9497	0.9291
66_RR_COL	Predominant color of the tuberous root surface	0.7729	0.1192
70_RR_COLP	Predominant color of tuberous root pulp	0.1475	0.8095
73_RR_COLSP	Secondary color tuberous root pulp	0.2217	0.8129
4_P_AERkg	Total weight of aerial part leaf + petiole (kg)	0.3915	0.3333
5_HJ_PESkg	Total leaf weight (kg)	0.4375	0.2969
9_PE_N	Number of petioles (unit)	0.5255	0.2704
18_CP_PESkg	Total weight of stock (kg)	0.3854	0.0079
22_RR_PESkg	Total weight of tuberous roots (kg)	0.4950	0.0011

*Bold cosine squared values indicate significant differences at 0.01% and underlines are identified as discriminant variables for the three cultivars.

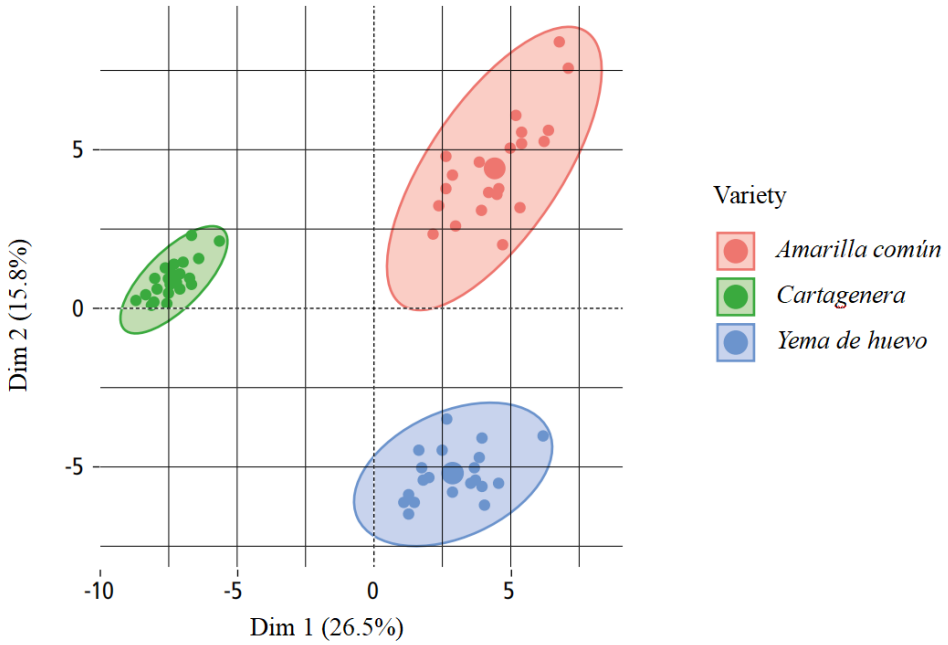

Figure 1. Ordering of 60 plants in a two-dimensional space of three arracacha cultivars based on AFMD analysis of 55 morphoagronomic characters in Cajamarca, Tolima, Colombia (2016 and 2018).
Dim 1: dimension 1; Dim 2: dimension 2.

According to Tabares[24], when characterizing morphoagronomically 39 accessions of arracacha collected in the Eje Cafetero ecoregion for identification and selection of promising genotypes, five qualitative variables considered as primary and secondary color of leaflet, petiole color, propagule color and tuberous root color, and 9 quantitative variables: leaf length and width, petiole number, propagule number and weight, leaf weight, vine size, and total weight and individual weight of commercial roots.

In this regard, Quilapanta *et al.*[4] found 11 discriminating morphological characters, including terminal leaflet acumen, terminal leaflet dissection, petiole waxiness, petiole striae, petiole striae, collinus pulp secondary color, collinus pulp color distribution, collinus pulp secondary color distribution, reservoir root shape, reservoir root pulp secondary color, collinus pulp color distribution and number of leaflets/leaf that allowed them to clearly differentiate the phenotypic characteristics of three materials of *A. xanthorrhiza*. These authors point out that the qualitative characters referred to the color of the different organs of the plant have a high weight in the differentiation of arracacha genotypes, except in the color of the reservoir root where no noticeable change is reflected. The mechanisms associated with coloration are due to the accumulation of anthocyanins in the epidermal cells where the genes responsible for color transcripts are expressed[23].

3.2 Phenotypic description of cultivars

3.2.1 *Amarilla común*

The plants reached up to 82 cm in height, but in commercial cultivation larger plants have been found. They have erect growth habit and medium size, the foliage is compact and intermediate with vigorous and leafy appearance of green and dark green, have a crown diameter of 126 cm. On average, they have 83 compound leaves 26.1 cm wide and 22.7 cm long with three or four pairs of broadly acuminate and elongated leaflets, with a cartate texture, moderately incised edge and without differentiated coloration. The upper side of the leaves are light green (5GY3/4) with light greenish yellow veins, the underside is olive green and light olive green (5GY4/4, 5GY4/8, 5GY5/4, 5GY5/6) without secondary coloration. The petioles have a length of 36.2 cm and total fresh weight of 0.5 kg with yellowish green coloration. The propagules have deep purple-red external coloration (5RP3/6, 5RP3/8, 5RP3/10), the flesh is yellow (5Y8/4, 5Y8/6) and sometimes the cortical ring is purple. The plant has 17 viable propagules for planting with a total weight of 300 g, length 7.49 cm and width 3.06 cm; it also produces 15 non-viable tillers for planting. The vine has a weight of 1.27 kg, horizontal length of 21.13 cm and vertical length of 13.84 cm. The tuberous roots are conical in shape, the external part is light yellow (5Y6/6, 5Y8/4, 5Y8/6) and grayish purple red (5RP4/6); the color of the pulp is light yellow (5Y6/6, 5Y8/6, 5Y8/8), grayish dark purple red (5RP3/4, 5RP4/6). A plant produces on average 10.7 tuberous roots, of which 6.4 are commercial and 4.3 are non-commercial. Commercial roots have a total weight of 1.72 kg per plant, individual weight of 268 g, 15.2 cm in length and 6 cm in width (**Figure 2A**).

3.2.2 *Yema de huevo*

The plants reached up to 56 cm in height, have erect growth habit and medium size, the foliage is medium and not very abundant, compact and intermediate light green; they have a crown diameter of 97 cm. On average they have 50 compound leaves 22.7 cm wide and 22.3 cm long with 2 to 3 pairs of leaflets. The upper side of the leaves is dark yellowish green (5GY4/6, 5GY4/4) with light green veins, the underside is opaque olive green (5GY5/4, 5GY5/6) with no secondary coloration. White dot-like pigmentations are present on each terminal leaflet margin, occasionally there is no evidence of pigmentation. The petioles have a length of 32.6 cm and total fresh weight of 0.5 kg, have a strong yellowish green coloration (5GY6/6, 5GY6/8, 5GY7/8, 2.5GY6/8, 2.5GY5/8) and in the basal part exhibit an intense pink to light pink coloration. The propagules have a moderate purplish-red external coloration (5RP4/8, 5RP4/10) and the flesh is dark yellow (5Y8/6, 5Y8/8). The plant has 16 viable propagules for planting with a total weight of 200 g, 6.43 cm

long and 2.57 cm wide; it also produces 8 non-viable tillers for planting. The vine has a weight of 1.14 kg, horizontal length of 21.45 cm and vertical length of 13.96 cm. The tuberous roots are conical in shape, the external part has a light yellow color (5Y8/4, 5Y8/6), the color of the pulp is intense yellow (5Y8/6-5Y8/8), which differentiates a cortical ring that simulates an egg yolk with a light yellow color (2.5Y8/6, 2.5Y8/8). A plant produces an average of 9.4 tuberous roots, of which 7.3 are commercial and 2.1 are non-commercial. Commercial roots have on average a total weight of 1.77 kg per plant, a length of 16 cm, diameter of 4.9 cm and individual weight of 235 g (**Figure 2B**).

3.2.3 *Cartagenera*

The plants reached an average height of 53 cm with a medium size, the foliage is intermediate and lax with a dark green color and the crown has a diameter of 89.7 cm. On average they have 35 compound leaves with 22.4 cm wide and 24.4 cm long with 4 to 5 pairs of opposite lateral leaflets and one terminal. The upper side of the leaves are dark olive green (5GY3/4) with purplish red veins (10R3/4, 10R4/4), the underside is olive green (5GY4/4, 5GY4/6, 5GY5/4) with purplish red veins and margins (5R3/4). In juvenile stage the leaves are greenish purple and in very advanced stages they are dark green. The petioles are 25.6 cm long and purplish red (5R3/4) throughout the structure. The propagules are dark red on the outside (5R3/6, 5R3/8) and cream (5Y8/4, 5Y8/6, 5Y8/8) in the flesh, 13 are viable for planting with a total weight of 100 g, length 6.78 cm and width 2.54 cm and 8 tillers are not viable. The vine has a weight of 0.7 kg, horizontal length of 18.57 cm and vertical length of 12.74 cm. The tuberous roots are conical in shape, the external part and the pulp are light yellow (5Y8/2, 5Y8/4) without secondary pigmentation. A plant produces an average of 8.5 tuberous roots of which 4.3 are commercial and 4.2 are non-commercial. Commercial roots have a total weight of 0.56 kg, individual weight of 128 g, 12.2 cm in length and 4.3 cm in width (**Figure 2C**).

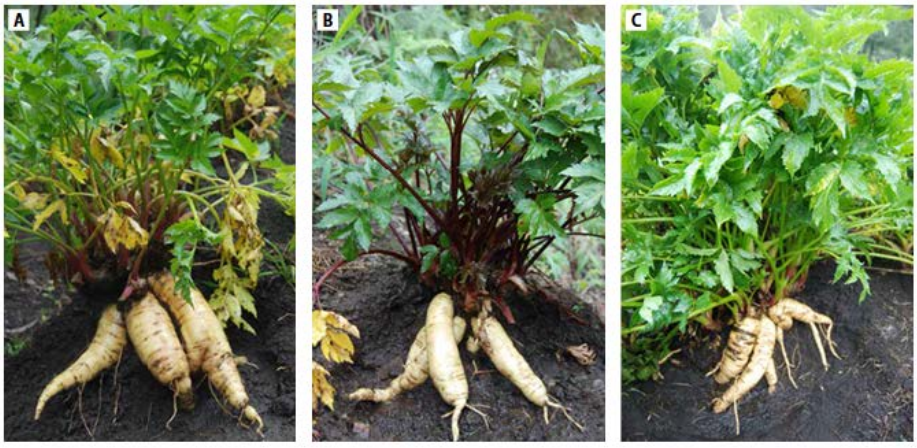

Figure 2. Arracacha cultivars evaluated in Cajamarca, Tolima, Colombia.
A. *Amarilla común* B. *Yema de huevo* C. *Cartagenera*

4. Conclusions

A complete morphological characterization of the regional cultivars *amarilla común*, *yema de huevo* and *cartagenera* is presented, and each plant structure or formation is described qualitatively and quantitatively. This study is the first characterization of regional cultivars in Colombia.

According to the mixed data factor analysis (MDFA), 8 quantitative variables were identified: foliage color, leaf bundle color, petiole color, external color of the propagule, color of the propagule base, predominant color of the propagule pulp, predominant color of the tuberous root pulp, secondary color of the tuberous root pulp; and 3 quantitative variables including number of petioles, leaf weight and tuberous root weight, which were selected as discriminants for phenotypic differentiation between *amarilla común*, *yema de huevo* and

cartagenera cultivars. These variables can be used in processes of morphoagronomic characterization of arracacha materials.

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Conflict of interest

The authors declared no conflict of interest.

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