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Granulometric characterization and grain size variability of quinoa (*Chenopodium quinoa* Willd.) genotypes in Cauca, Colombia

Caracterización granulométrica y variabilidad del tamaño de grano en genotipos de quinua (*Chenopodium quinoa* Willd.) en Cauca, Colombia

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ABSTRACT

Granulometric characterization is a fundamental tool for differentiating quinoa (*Chenopodium quinoa* Willd.) genotypes with physical and productive attributes of interest for genetic improvement and agro-industrial competitiveness. However, in Colombia, studies integrating grain-size distribution with yield-related variables remain limited, restricting the selection of materials that combine productivity with superior physical grain quality for specialized markets. This study aimed to evaluate yield, grain weight, thickness, and granulometric distribution in four genotypes (Fam37, Fam56, Fam110, and the commercial check Blanca de Jericó) established in La Palma village, Totoro municipality (Cauca, Colombia), under a randomized complete block design with four replications. Grain yield per plant, thousand-seed weight, grain weight and percentage retained on 1.7, 1.4, and 1.0 mm sieves, and grain thickness within each fraction were measured. Data were analyzed using analysis of variance (ANOVA) followed by Tukey's test (P<0.05), in addition to linear regression models. ANOVA revealed highly significant differences (P<0.001) for all variables. Fam56 showed the highest yield (30.9 g per plant), Fam37 exhibited the highest thousand-seed weight (2.99 g) and the greatest proportion retained on the 1.7 mm sieve (15.75 g; 59.05%), whereas Fam110 presented the greatest grain thickness (1.20 mm) and a more uniform distribution. Regression models indicated that thousand-seed weight explained 81% of the variation in grain weight and 75% of the percentage retained on the 1.7 mm sieve (P<0.001), demonstrating its usefulness for seed conditioning and commercial grain grading, as well as for supporting selection decisions in breeding programs. These results indicate that Fam37 and Fam56 combine high yield with superior physical grain quality, highlighting their potential as promising materials for breeding and agro-industrial applications.

RESUMEN

Palabras clave:
Calibre de grano
Fracciones granulométricas
Calidad física del grano
Tamizado
Peso de mil semillas
Rendimiento

La caracterización granulométrica constituye una herramienta fundamental para diferenciar genotipos de quinua (*Chenopodium quinoa* Willd.) con atributos físicos y productivos de interés para el mejoramiento genético y la competitividad agroindustrial. Sin embargo, en Colombia aún son limitados los estudios que integran la distribución granulométrica del grano con variables de rendimiento, lo cual restringe la selección de materiales que combinen productividad y calidad física para mercados especializados. El objetivo de este estudio fue evaluar el rendimiento, el peso, el espesor y la distribución granulométrica del grano en cuatro genotipos (Fam37, Fam56, Fam110 y el testigo comercial Blanca de Jericó) establecidos en La Palma, municipio de Totoro (Cauca, Colombia), bajo un diseño de bloques completos al azar con cuatro repeticiones. Se midieron la producción por planta, el peso de mil semillas, el peso y porcentaje de grano retenido en tamices de 1,7, 1,4 y 1,0 mm, y el espesor en cada fracción. Los datos se analizaron mediante análisis de varianza (ANOVA) y prueba de Tukey (P<0,05), además de modelos de regresión lineal. El análisis de varianza reveló diferencias altamente significativas (P<0,001) para todas las variables. Fam56 presentó el mayor rendimiento (30,9 g por planta), Fam37 destacó por el mayor peso de mil semillas (2,99 g) y mayor proporción de grano retenido en 1,7 mm (15,75 g; 59,05%), mientras que Fam110 exhibió el mayor espesor (1,20 mm) y una distribución más uniforme. Los modelos de regresión indicaron que el peso de mil semillas explicó el 81% de la variación en el peso y el 75% del porcentaje retenido en 1,7 mm (P<0,001), evidenciando su utilidad para el acondicionamiento y la clasificación comercial del grano, así como para apoyar decisiones de selección en programas de mejoramiento. Se concluye que Fam37 y Fam56 combinan alto rendimiento y calidad física, siendo materiales promisorios para el fitomejoramiento y la agroindustria.

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The Andean region of South America, encompassing Peru, Bolivia, Ecuador, and Colombia, is one of the world's principal centers of agricultural diversification, characterized by remarkable genetic and cultural richness (Pandya et al. 2023). Within this context, extensive germplasm collections of tubers, vegetables, fruits, cereals, and pseudocereals—traditionally grouped as Andean crops—are preserved (Salazar et al. 2021). These species have historically evolved under marginal agroecological conditions, contrasting with large-scale production systems dominated by maize, wheat, and rice (Pinto-Irish et al. 2020).

Among them, quinoa (*Chenopodium quinoa* Willd.) has achieved global relevance due to its exceptional nutritional profile and high adaptive plasticity under extreme environments (Angeli et al. 2020; Schmidt et al. 2021). Its balanced composition of macronutrients (11–20% protein, 5–10% lipids, and 45–78% complex carbohydrates), along with all nine essential amino acids, minerals, and B-group vitamins, positions it as a functional food capable of addressing current food security challenges (Rehman et al. 2022; Taaime et al. 2023).

Climate change and the expansion of agriculture into new productive frontiers have intensified the search for quinoa genotypes with early maturity, high yield potential, and superior grain quality capable of maintaining nutritional and functional stability under variable environmental conditions (Lozano-Isla et al. 2023). In this context, the evaluation of physical grain traits such as size, thickness, and weight has become increasingly relevant, as these attributes directly influence agronomic performance, seed grading, and industrial processing efficiency. Grain size uniformity and thickness are particularly important parameters determining commercial acceptance and technological quality in high-value markets (Habib et al. 2024).

Grain-size distribution is widely used in post-harvest grading and seed conditioning because it determines the proportion of premium fractions and influences technological performance during processing. Accordingly, traits such as thousand-seed weight, grain thickness, and sieve retention provide practical information for identifying genotypes that meet quality requirements in specialized value chains (De Bock et al. 2021; Lozano-Isla et al. 2023). Beyond market preference, physical grain caliber can affect industrial suitability because it influences the efficiency and uniformity of post-harvest operations and the standardization of grain lots destined for food processing. In quinoa, studies assessing diverse germplasm and improved materials have highlighted that grain physical attributes and yield-related traits can jointly support decisions for selection and commercialization across contrasting production environments (Ren et al. 2024; Anchico-Jojoa et al. 2023).

Quinoa exhibits broad ecotypic diversity, classified into five main adaptive groups: valley, altiplano, salares, sea-level, and subtropical, reflecting its ecological versatility (Taaime et al. 2023). In Colombia, the crop is cultivated between 2,000 and 4,000 meters above sea level (masl), covering approximately 2,500 ha with an annual production near 4,781 t (Schmidt et al. 2021). However, despite advances in morpho-agronomic characterization, national studies integrating grain granulometric parameters with regression-based associations between physical traits and productive performance remain scarce. This limitation constrains breeding programs from selecting materials that simultaneously combine high yield and physical grain quality aligned with agro-industrial requirements and international standards (Pizo et al. 2024).

In key producing regions such as Cauca, Nariño, and Boyaca, where most national production is concentrated, identifying genotypes with a higher proportion of large and thick grains represents a strategic opportunity to enhance competitiveness within specialized value chains (Pizo et al. 2025). Therefore, the aim of this study was to evaluate yield, grain thickness, and grain-size distribution across sieve fractions in three sweet-quinoa families and a commercial check under field conditions in Totoro (Cauca, Colombia), and to quantify regression-based relationships between grain physical parameters and productive performance. It was hypothesized that genotypes with higher thousand-seed weight and a larger proportion of grains retained in the 1.7 mm fraction would exhibit superior physical grain quality and higher yield potential, supporting their identification as promising materials for breeding and agro-industrial use under Colombian conditions.

MATERIALS AND METHODS

Location and plant material

The study was conducted in La Palma village, Totoro municipality (Cauca, Colombia) (2°33'46.37" N, 76°34'28.30" W), at an altitude of 2,280 meters above sea level (masl). The area is characterized by an average annual temperature of 15 °C, annual rainfall of approximately 1,300 mm, and 85% relative humidity. The experiment was established during the second cropping period of 2024.

The plant material consisted of three sweet-quinoa experimental families (Fam37, Fam56, and Fam110) derived from Aurora × Tunkahuan progeny (Figure 1), developed within a local breeding scheme aimed at improving yield and physical grain quality. These families were selected due to their contrasting agronomic performance and grain-size profiles. The commercial cultivar Blanca de Jericó was included as a regional reference (commercial check) because it is widely cultivated in the study area and represents the local standard for comparison (Table 1).

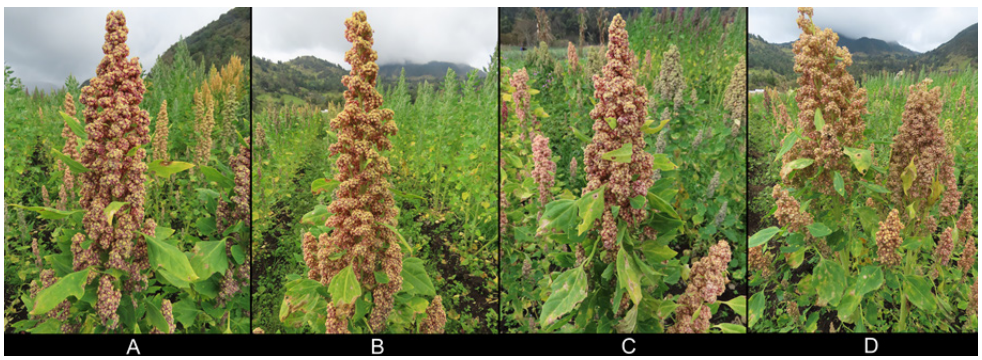


Figure 1. Field phenotypic variation among quinoa (Chenopodium quinoa Willd.) genotypes included in the granulometric characterization: (A) Fam 37, (B) Fam 56, (C) Fam 110, and (D) Blanca de Jericó.

Table 1. Plant material evaluated in the study and origin.

Genotype	Type of material	Genetic background / origin	Role in the trial
Fam37	Sweet-quinoa family	Aurora×Tunkahuan progeny (experimental cross)	Experimental genotype
Fam56	Sweet-quinoa family	Aurora×Tunkahuan progeny (experimental cross)	Experimental genotype
Fam110	Sweet-quinoa family	Aurora×Tunkahuan progeny (experimental cross)	Experimental genotype
Blanca de Jericó	Commercial cultivar	Widely cultivated in Cauca, Colombia	Commercial check

Experimental design, agronomic management, and harvest procedures

The field trial was initially established with 17 quinoa genotypes under a randomized complete block design (RCBD) with four replications, covering a total experimental area of 261 m². Each experimental unit consisted of a 3-m row, with 0.70 m between rows and 0.10 m between plants (30 plants per row). For the present granulometric assessment, four genotypes were selected from this trial (Fam37, Fam56, Fam110, and the commercial check Blanca de Jericó) based on superior agronomic performance in the initial evaluation; this subset was subsequently used to quantify grain-size distribution and physical grain quality traits. To minimize border effects, all measurements and harvest samples were obtained from the same central 2-m section of each plot, discarding border plants. With 0.70 m row spacing, the plot area was 2.1 m² (3.0×0.70 m).

Quinoa grain size typically spans approximately 1.0–2.6 mm, although this range varies across genotypes and environments. Sieve-based grading using meshes within ~1.0–2.0 mm is widely applied in seed conditioning and post-harvest classification to describe grain-size distributions and separate commercial fractions. Accordingly, the 1.7, 1.4, and 1.0 mm sieves used here enabled a practical classification of large, medium, and small fractions for comparative purposes (Ren et al. 2024).

Fertilization management was defined based on a pre-establishment soil analysis. Organic fertilization consisted of compost produced by co-composting sugarcane filter cake (cachaza) and poultry manure, incorporated into the soil 20 days before sowing to improve soil physical and chemical properties and ensure adequate mineralization. During the crop cycle, an aerobically fermented liquid organic fertilizer (A.L.O.F.A.) was applied every 20 days as both foliar spray and root drench at 50 mL L^{-1} (equivalent to 1 L per 20-L knapsack sprayer) per application, as part of an agroecological strategy to sustain nutrient availability throughout crop development.

To maintain agroecological conditions without herbicides, weed control relied on three manual weeding operations during the experimental period to reduce competition for light, nutrients, and water (Pizo et al. 2025). Thinning was performed 35 days after sowing (plants ~15 cm tall) by removing weak individuals to promote uniform stand establishment and reduce intra-specific competition. Hilling was carried out manually twice at approximately 30 and 70 cm plant height to improve anchorage, soil aeration, and crop stability.

Phytosanitary management was based on periodic scouting; when pest or disease symptoms were observed, control relied on agroecological inputs, specifically plant-based purines prepared from garlic, chili pepper, and onion, applied as needed to reduce incidence and limit further spread. Collectively, these practices were implemented to standardize field conditions across treatments, so that observed differences among genotypes primarily reflected genetic effects and their interaction with the climatic and edaphic conditions of the Totoro region.

Harvesting was conducted at physiological maturity based on seed color, texture, and the fingernail test. Plants from the sampled section were cut with pruning shears and labeled by genotype and panicle number. The harvested material was air-dried for 15–20 days, manually threshed, cleaned using calibrated sieves, and stored in sealed bags before being transported to the AGROSAVIA Seed Laboratory (Popayan) for physical and agronomic evaluation.

Yield variables and grain measurements

Yield and physical grain-quality traits were selected to jointly represent agronomic performance and post-harvest grading attributes relevant to breeding and agro-industrial use (Table 2). Yield per plant and thousand-seed weight were recorded as standard indicators of productivity and seed size. Grain-size distribution was quantified through sieve classification by measuring the dry grain weight and percentage retained on 1.7, 1.4, and 1.0 mm meshes, which represent large, medium, and small commercial fractions, respectively. Grain thickness was subsequently measured within each fraction as a complementary physical-quality trait linked to grain density and technological performance. Field data were obtained from harvested plants within each experimental plot, whereas granulometric classification and thickness determinations were performed on cleaned grain samples in the laboratory following the procedure described below.

For each experimental plot, grain samples were cleaned and homogenized prior to granulometric classification. Granulometry was conducted using one dry subsample per plot (one sieving run per plot) across the 1.7, 1.4, and 1.0 mm meshes. The dry weight retained in each fraction was recorded, and percent retention was calculated on a dry-weight basis as shown Table 2.

Sieving procedure

Granulometric characterization was carried out using a vibration-controlled electric sieve shaker (Pinzuar®, Colombia) equipped with calibrated meshes of 1.7, 1.4, and 1.0 mm. The process was performed under stable environmental conditions (25±2 °C; 60±5% relative humidity). Each subsample was sieved for three minutes, and the resulting fractions were weighed on an analytical balance (Mettler Toledo®, Switzerland) to ensure precision and reproducibility in determining grain weight and relative proportion.

Statistical analysis

Descriptive statistics (mean and coefficient of variation) were computed for all variables. Prior to inferential analyses, ANOVA assumptions were evaluated by assessing residual normality and homogeneity of variances. When these assumptions were satisfied, treatment means were compared using analysis of variance (ANOVA) under the randomized complete block design, and mean separation was performed with Tukey's test at $P<0.05$. In addition,

Table 2. Variables and measurement methods for yield and physical grain quality in four quinoa genotypes.

Variable	Unit	Source	Description
Yield per plant	g	Field	Twenty plants randomly selected from the central part of each plot were weighed using an analytical balance.
Thousand-seed weight	g	Laboratory	Weight of thousand-seed determined with a precision analytical balance.
Grain weight retained (1.7 mm)	g	Laboratory	Classification and weighing using an electric sieve shaker (Pinzuar®) fitted with calibrated meshes (1.7, 1.4 and 1.0 mm).
Grain weight retained (1.4 mm)	g	Laboratory	
Grain weight retained (1.0 mm)	g	Laboratory	
Percentage retained (1.7 mm)	%	Laboratory	Proportion retained on the 1.7 mm sieve relative to total sample weight.
Percentage retained (1.4 mm)	%	Laboratory	Proportion retained on the 1.4 mm sieve relative to total sample weight.
Percentage retained (1.0 mm)	%	Laboratory	Proportion retained on the 1.0 mm sieve relative to total sample weight.
Grain thickness (1.7 mm fraction)	mm	Laboratory	Measured with a digital caliper on grains from the 1.7 mm fraction.
Grain thickness (1.4 mm fraction)	mm	Laboratory	Measured with a digital caliper on grains from the 1.4 mm fraction.
Grain thickness (1.0 mm fraction)	mm	Laboratory	Measured with a digital caliper on grains from the 1.0 mm fraction.

simple linear regression models were fitted to evaluate relationships among thousand-seed weight, the weight and proportion of grain retained on the 1.7 mm sieve, grain thickness, and yield per plant. For regression analyses, statistical significance was assessed at $P<0.05$, and highly significant relationships were additionally reported at $P<0.001$ when applicable. The general form of the regression (Equation 1) was:

$$Y=\beta_0+\beta_1X \quad (1)$$

Where Y is the response variable, X is the predictor, β_0 is the intercept, and β_1 is the slope. Analyses were conducted in R v4.5 using stats (ANOVA and linear models) and agricolae (Tukey mean separation), and figures were produced with ggplot2.

RESULTS AND DISCUSSION

The analysis of variance (ANOVA) showed highly significant differences among the four quinoa genotypes for all variables related to yield and physical grain quality (Table 3).

Table 3. Analysis of variance (ANOVA) results for yield and physical grain traits in quinoa genotypes.

Variables	Source of variation	F	*p-value*
Yield per plant (g)	Genotype	11.76	0.0018**
	Block	0.93	0.4632
	Total		
Thousand-seed weight (g)	Genotype	34.04	<0.0001***
	Block	0.64	0.6077
	Total		
Grain thickness- 1.7 mm sieve	Genotype	10.56	<0.0001***
	Block	4.56	0.0076
	Total		

Table 3.

Variables	Source of variation	F	*p-value*
Grain thickness- 1.4 mm sieve	Genotype	7.17	<0.006**
	Block	0.89	0.4544
	Total		
Grain thickness- 1 mm sieve	Genotype	7.66	<0.004**
	Block	1.55	0.216
	Total		
Grain weight (g)- 1.7 mm sieve	Genotype	34.36	<0.0001***
	Block	0.51	0.6824
	Total		
Grain weight (g)- 1.4 mm sieve	Genotype	26.34	<0.0001***
	Block	1.41	0.3031
	Total		
Grain weight (g)- 1 mm sieve	Genotype	2.22	<0.0045**
	Block	0.9	0.4798
	Total		
Percentaje retained (%)- 1.7 mm sieve	Genotype	60.69	<0.0001***
	Block	0.3	0.8233
	Total		
Percentaje retained (%)- 1.4 mm sieve	Genotype	20.76	<0.0002***
	Block	0.26	0.8542
	Total		
Percentaje retained (%)- 1 mm sieve	Genotype	6.94	<0.0102*
	Block	0.96	0.4511
	Total		

Yield per plant and thousand-seed weight differed significantly among genotypes ($P<0.05$) (Figure 1). Fam56 showed the highest yield (30.9 g per plant), whereas the commercial check Blanca de Jericó recorded the lowest yield (17.9 g per plant). Regarding thousand-seed weight, Fam37 presented the highest value (2.99 g), while Blanca de Jericó showed the lowest (2.19 g); Fam110 (2.85 g) and Fam56 (2.83 g) exhibited intermediate values (Figure 2).

Fam56 reached the highest yield (30.9 g per plant), reflecting greater efficiency in capturing and using soil and environmental resources, which favored both biomass accumulation and grain filling. This behavior agrees with findings in Brazil and Colombia (Vergara et al. 2020), which attribute high yields to greater physiological capacity to capture water, nutrients, and radiation, as well as to the combined effects of genetic vigor and agronomic management (Estrada-Zúniga et al. 2022; Chura et al. 2019; Ren et al. 2024; Reynolds et al. 2020). The value obtained exceeded reports by Chura et al. (2019) and Estrada-Zúniga et al. (2022) in Bolivia and Perú (20.4 and 27.9 per plant, respectively), and those by Delgado et al. (2024) (22.3 - 26.8 per plant) and fell within the upper range recorded for adapted materials in Brazil and Colombia (29.8 and 31.2 per plant, respectively).

The joint analysis of yield and thousand-seed weight reaffirms the usefulness of the latter as an indirect selection criterion in *C. quinoa* (Pizo et al. 2025; Lozano-Isla et al. 2023; Habib et al. 2024). Fam37 reached 2.99 g, above the reported range for the species (2.03–2.87 g), evidencing greater density, size, and grain filling, attributes influenced by genetic and physiological factors and genotype ×

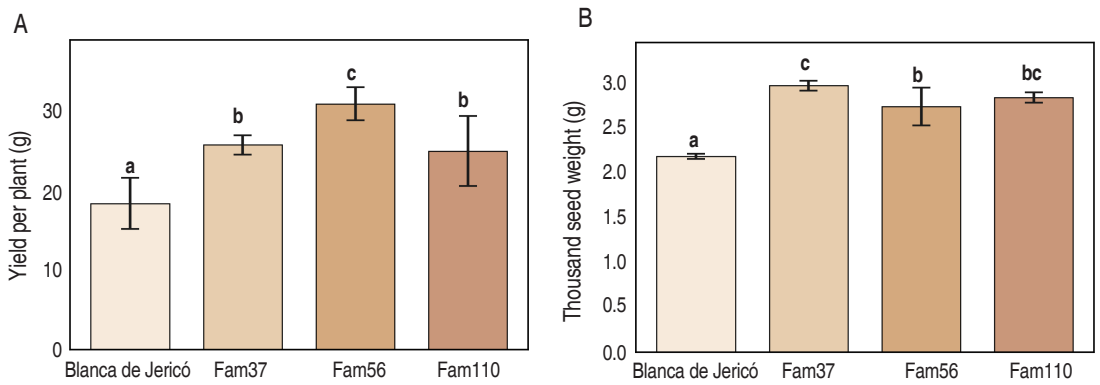


Figure 2. A). Yield per plant and B). Thousand-seed weight in four *Chenopodium quinoa* genotypes. Different letters above bars indicate statistically significant mean differences according to Tukey's test ($P<0.05$).

environment interaction (Salazar et al. 2021). This trait is associated with greater thickness and competitiveness in specialized markets (Chura et al. 2019; Estrada-Zúniga et al. 2022) and is also key for commercial acceptance and seeding calibration (Reynolds et al. 2020; Manjarres-Hernández et al. 2022). Fam110 (2.85 g) and Fam56 (2.83 g) were within reference values, retaining potential for high-value niches (Ren et al. 2024).

Grain weight and percentage retained across sieve fractions in *C. quinoa*

Grain weight and the percentage retained across sieve fractions differed significantly among genotypes ($P<0.05$) (Figure 3). For grain weight retained on the 1.7 mm sieve (Figure 3A), Fam37 showed the highest value (15.75 g), whereas the commercial check Blanca de Jericó recorded the lowest (2.23 g); Fam56 (10.20 g) and Fam110 (8.64 g) exhibited intermediate values. In the 1.4 mm fraction (Figure 3B), Fam56 presented the highest grain weight (18.51 g), while Fam37 showed the lowest (10.33 g). In the 1.0 mm fraction (Figure 3C), Blanca de Jericó exhibited the highest weight (4.00 g), whereas Fam37 recorded the lowest (0.87 g), indicating a greater proportion of small grains in the commercial check.

Regarding percentage retained, Fam37 presented the highest value on the 1.7 mm sieve (59.05%), while Blanca de Jericó showed the lowest (10.77%) (Figure 3D). At 1.4 mm (Figure 3E), Blanca de Jericó exhibited the highest proportion (69.54%), whereas Fam37 recorded the lowest (38.39%). Finally, at 1.0 mm (Figure 3F), Blanca de Jericó again showed the highest value (12.31%), while Fam37 exhibited the lowest (2.40%).

The distribution of grain weight across granulometric fractions is a key indicator of agronomic potential and physical quality in *C. quinoa* (Ren et al. 2024). In this study, Fam37 showed the greatest grain weight retained on the 1.7 mm sieve, consistent with higher yield potential, processing efficiency, and market preference. This performance exceeded ranges reported in Bolivia and Ecuador (9.8–13.2 g and 11.1–13.9 g, respectively) (Chura et al. 2019; Estrada-Zúniga et al. 2022) and was comparable to findings under Brazil and Colombia conditions (Anchico-Jojoa et al. 2023). Biologically, the dominance of the 1.7 mm fraction suggests more efficient grain filling and reserve deposition, where starch accumulation in the main storage tissue contributes to final grain mass and physical grain quality (Pinto-Irish et al. 2020; López-Cervantes et al. 2021). Agronomically and commercially, this pattern is relevant because sieve-based grading is routinely used for post-harvest standardization, and proposed international thresholds classify grains retained above 1.7 mm as large fractions and those between 1.4–1.7 mm as medium fractions, reinforcing the value of increasing the 1.7 mm proportion for high-value markets.

At the genetic level, the contrasts among families indicate exploitable variation for grain-size distribution, supporting Fam37 as a promising parental source to increase the frequency of large-grain fractions, consistent with multi-environment evidence that seed-size traits can be improved

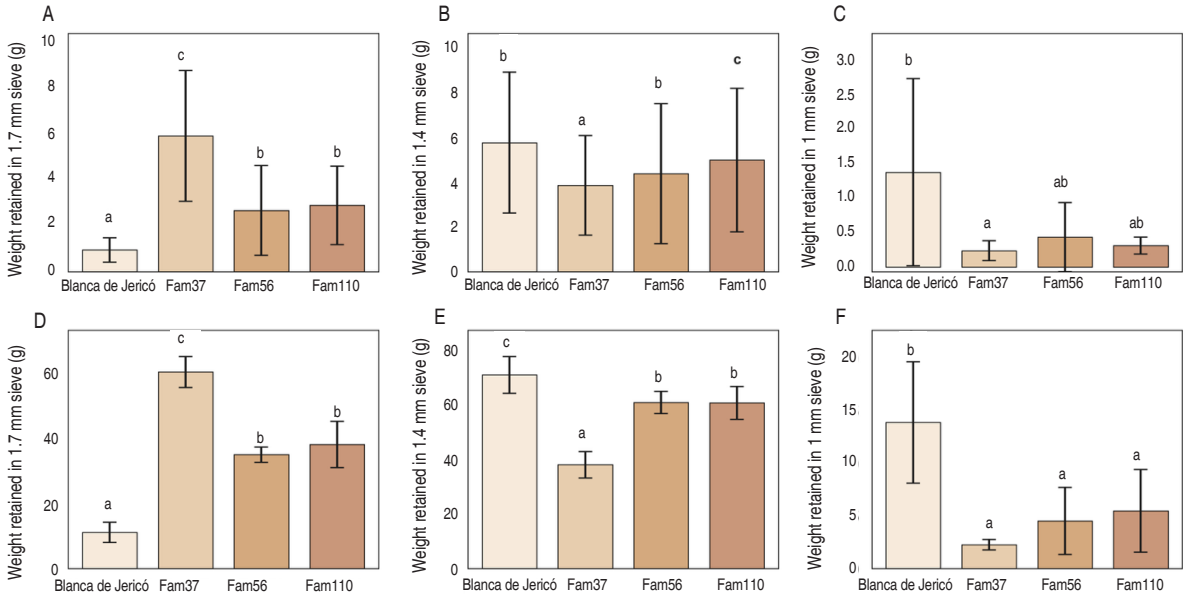


Figure 3. Classification of four *C. quinoa* genotypes by grain weight retained in 1.7 mm (**A**), 1.4 mm (**B**), and 1.0 mm (**C**) sieves, and percentage retained in the same fractions (**D, E, F**). Different letters indicate statistically significant mean differences according to Tukey's test (P<0.05).

through selection and crossing (Estrada-Zúniga et al. 2022; Anchico-Jojoa et al. 2023). Moreover, genome-wide association studies confirm that thousand-seed weight and related seed-size traits are quantitatively controlled and linked to candidate genomic regions, supporting recurrent selection strategies to improve grain caliber (Habib et al. 2024). Fam56 exhibited a balanced profile dominated by the 1.4 mm fraction and a low proportion of small grains, consistent with size uniformity and resilience under variable environments (Habib et al. 2024). Fam110 showed a homogeneous distribution across fractions, similar to adapted materials maintaining stable physical quality across contrasting edaphoclimatic conditions, which is advantageous for selection and recommendation (Estrada-Zúniga et al. 2022; Manjarres-Hernández et al. 2022; Anchico-Jojoa et al. 2023). In contrast, Blanca de Jericó concentrated more grain in the 1.0 mm fraction (4.0 g), suggesting incomplete filling and a higher share of small grains, which can reduce competitiveness and processing standardization in premium markets (Lozano-Isla et al. 2023; Arguello-Hernández et al. 2024).

In percentage terms, Fam37 also retained the highest value at 1.7 mm, surpassing maxima reported elsewhere (45–53%) (Chura et al. 2019; Estrada-Zúniga et al. 2022). While this reinforces its value for breeding aimed at increasing grain size, grain caliber remains polygenic and requires targeted crossing and recurrent selection to fix favorable alleles (López-Cervantes et al. 2021). Accordingly, Fam56 and Fam110 represent useful base materials for consolidating stable attributes (Estrada-Zúniga et al. 2022). Finally, agronomic management can modulate grain-size expression under stress; thus, integrating genetic selection with improved fertilization and water management is critical to stabilize desirable granulometric profiles under Colombian conditions (El-Harty et al. 2023).

Quinoa seed thickness

Grain thickness differed significantly among genotypes across all granulometric fractions (P<0.05) (Figure 4). In the 1.7 mm fraction (Figure 4A), Fam110 exhibited the greatest thickness (1.20 mm), whereas the commercial check Blanca de Jericó showed the lowest value (1.09 mm); Fam56 (1.18 mm) and Fam37 (1.15 mm) displayed intermediate values. In the 1.4 mm fraction (Figure 4B), Fam110 again showed the highest thickness (1.04 mm), while Blanca de Jericó recorded the lowest (0.89 mm). In the 1.0 mm fraction (Figure 4C), Fam110 presented the highest thickness (0.77 mm), whereas Blanca de Jericó showed the lowest (0.65 mm).

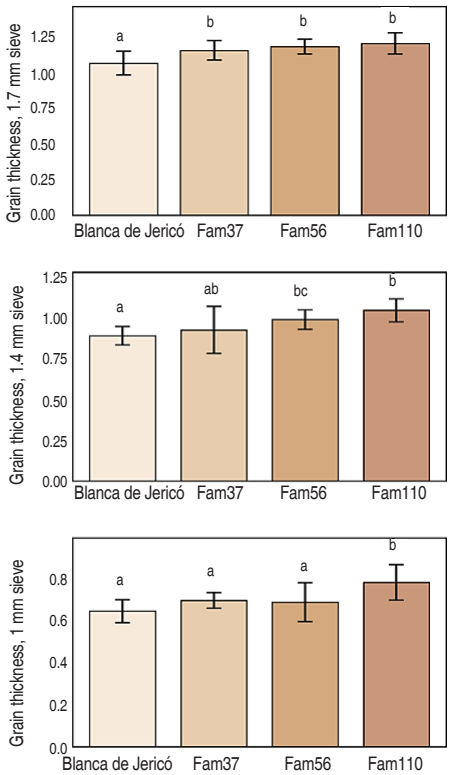


Figure 4. Grain thickness in three granulometric fractions. **(A)** 1.7 mm sieve**, (B)** 1.4 mm sieve, and **(C)** 1.0 mm sieve in four *C. quinoa* genotypes. Different letters indicate statistically significant mean differences according to Tukey's test ($P \leq 0.05$).

Grain thickness is a key physical quality attribute associated with grain density and technological performance, and thicker grains are often preferred in markets demanding large and uniform quinoa grains (Lozano-Isla et al. 2023; Anchico-Jojoa et al. 2023). The thickness values observed for Fam110 and Fam56 in the 1.7 mm fraction (>1.15 mm) are consistent with reports for high-quality materials evaluated under Andean and temperate environments (Chura et al. 2019; Estrada-Zúniga et al. 2022). Moreover, De Bock et al. (2021) highlighted that grain size fractions contribute substantially to yield and processing performance, supporting the relevance of thickness as a complementary trait for distinguishing promising genotypes.

The 1.7 mm sieve represents the largest-grain fraction, and thickness in this category is a practical indicator of physical quality linked to industrial yield and consumer preference in markets valuing large, uniform grains (Lozano-Isla et al. 2023; Anchico-Jojoa et al. 2023). In this study, Fam110 and Fam56 exceeded 1.15 mm, a threshold reported for high-quality commercial materials in Peru and Bolivia (Chura et al. 2019; Estrada-Zúniga et al. 2022), supporting their suitability for premium grain categories and for post-harvest grading aimed at increasing the share of marketable fractions. This interpretation is consistent with De Bock et al. (2021), who highlighted that large-grain fractions can contribute substantially to yield and processing performance, reinforcing thickness as a useful complementary trait in selection and commercialization.

Fam110 combined greater thickness with a homogeneous distribution across fractions, suggesting efficient grain filling and reserve accumulation (Ren et al. 2024). From a breeding perspective, this combination is desirable because it indicates a higher probability of obtaining progenies with stable physical grain quality across size classes, improving consistency for agro-industrial use. In contrast, Fam56 performed well in the large-grain fraction but showed

greater variability in smaller fractions, which may require complementary selection for uniformity depending on the target market. Fam37 showed stable thickness but slightly lower values in the premium fraction, which may translate into lower competitiveness in strict size-based grading schemes. Finally, Blanca de Jericó presented the lowest thickness values, which is consistent with a smaller-grain profile; despite its lower physical quality relative to improved families, it remains relevant as a locally adapted reference material for comparison and potential use in region-specific breeding goals (Ren et al. 2024).

Regression models

Linear regression models indicated that thousand-seed weight explained 33% of the variation in yield per plant (R^2=0.33; Figure 5A), 36% of the variation in grain weight retained on the 1.7 mm sieve (R^2=0.36; Figure 5B), and 75% of the variation in the percentage retained in that fraction (R^2=0.75; Figure 5C). Grain thickness in the 1.7 mm fraction showed a weak association with the percentage retained at 1.7 mm (R^2=0.16; Figure 5D), suggesting that thickness and sieve retention capture complementary dimensions of grain physical quality.

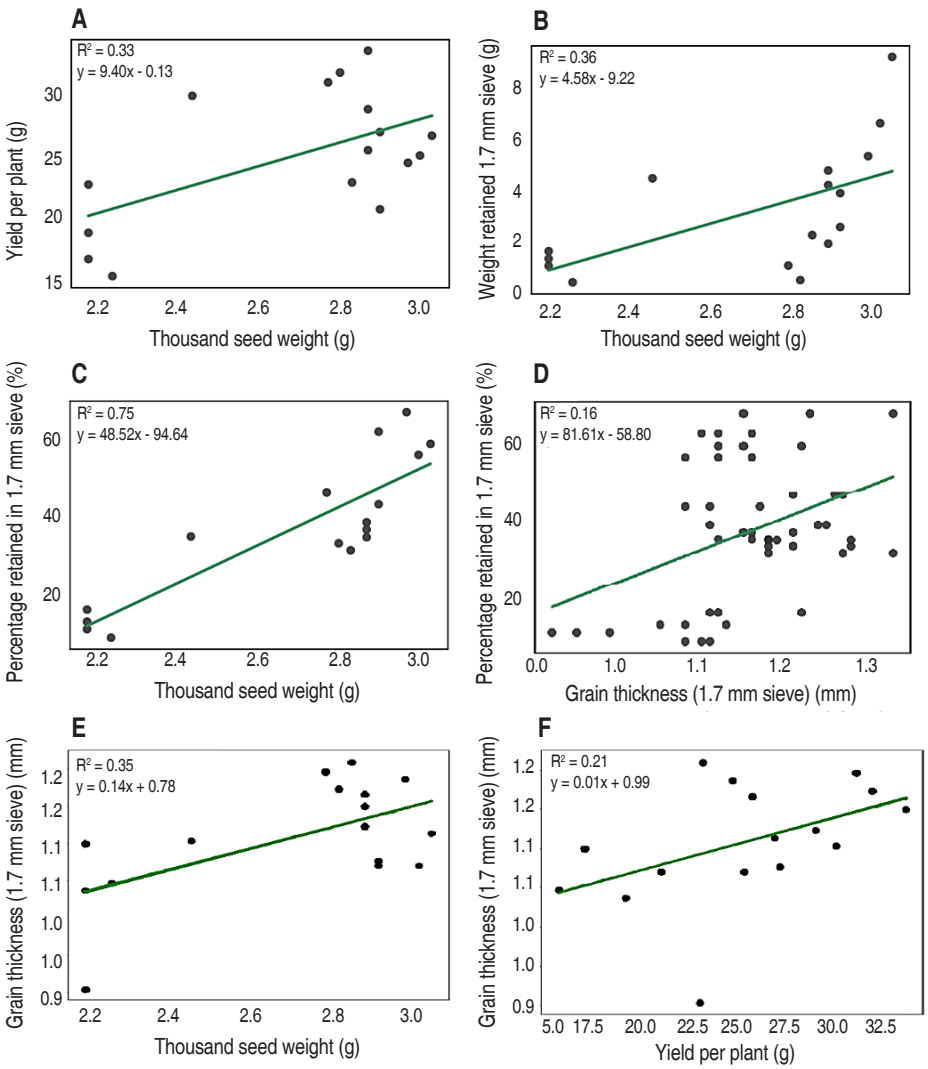


Figure 5. Relationships between thousand-seed weight, yield, and physical grain quality variables in *C. quinoa*. **A**) Yield per plant as a function of thousand-seed weight. **B**) Grain weight retained on the 1.7 mm sieve as a function of thousand-seed weight. **C**) Percentage retained on the 1.7 mm sieve as a function of thousand-seed weight. **D**) Percentage retained on the 1.7 mm sieve as a function of grain thickness in the 1.7 mm fraction. **E**) Grain thickness in the 1.7 mm fraction as a function of thousand-seed weight. **F**) Grain thickness in the 1.7 mm fraction as a function of yield per plant. Green lines represent the fitted linear regression for each relationship.

In addition, grain thickness was positively associated with thousand-seed weight (R^2=0.35; p=0.015; Figure 5E), indicating that thicker grains tend to be linked to heavier seeds. The relationship between grain thickness (1.7 mm fraction) and yield per plant was weaker and not statistically significant at P<0.05 (R^2=0.21; p=0.076; Figure 5F), suggesting that thickness may contribute to physical grain quality but is not a strong predictor of yield under the evaluated conditions.

The linear regression between thousand-seed weight and the grain weight retained on the 1.7 mm sieve (R^2=0.36; Figure 5B) is consistent with Silva-García et al. (2024) and Ren et al. (2024), who indicate that thousand-seed weight reflects the proportion of large grains—an attribute valued in gourmet markets and agro-industrial processes requiring uniformity and volume. In addition, thousand-seed weight showed a strong linear relationship with the percentage retained on the 1.7 mm sieve (R^2=0.75; Figure 5C), supporting the role of seed size in shaping granulometric profiles aligned with quality standards (FAO 2012) and corroborating studies linking larger and thicker grains with improved technological performance (Anchico-Jojoa et al. 2023; Arguello-Hernández et al. 2024).

The relationship between thousand-seed weight and yield per plant was moderate (R^2=0.33; Figure 5A), which is consistent with Manjarres-Hernández et al. (2021), who associate seed size with physiological efficiency during grain filling and, consequently, with yield. Grain thickness in the 1.7 mm fraction showed low explanatory power for the percentage retained on the 1.7 mm sieve (R^2=0.16; Figure 5D), suggesting that thickness and sieve retention represent complementary dimensions of grain physical quality rather than redundant metrics (De Bock et al. 2021; Taaime et al. 2023).

CONCLUSION

Granulometric characterization proved to be a precise and discriminating approach for identifying *Chenopodium quinoa* Willd. genotypes with contrasting physical and productive attributes. Among the evaluated traits, thousand-seed weight and the proportion of grains retained on the 1.7 mm sieve were strongly associated with grain-size distribution and physical grain quality, and they showed a moderate relationship with yield under the evaluated conditions. In particular, Fam56 achieved the highest yield (30.9 g per plant), while Fam37 presented the highest thousand-seed weight (2.99 g) and the greatest retention in the 1.7 mm fraction (59.05%), supporting their identification as the most promising materials when prioritizing simultaneous productivity and premium grain caliber. Fam110 exhibited the greatest grain thickness (1.20 mm) and a more uniform size distribution, indicating its value as complementary germplasm for improving grain physical quality traits within breeding schemes. Overall, these findings provide a methodological basis for incorporating sieve-based grain-size analysis into selection and seed-quality evaluation in Colombia. Future research should complement this work by assessing physiological and nutritional grain quality (e.g., starch and protein composition) associated with grain thickness and processing performance.

CONFLICT OF INTEREST

The authors declare that this is an original work and that they have no conflicts of interest regarding the preparation or publication of the manuscript.

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