



Sustainable valorization of discarded black quinoa (*Chenopodium quinoa*) grains: Impact of particle size on nutritional, functional, and antioxidant properties

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ABSTRACT

The valorization of agricultural co-products represents a promising strategy to reduce food waste while creating new functional ingredients for the food industry. This study aims to evaluate the potential of discarded black quinoa grains (commonly referred as "destrío" grains in Spain) as a novel source of functional flour, using particle size-milling to evaluate its influence on the nutritional and techno-functional properties. Four flours with different particle sizes were produced and characterized in terms of chemical composition, mineral profile, physicochemical properties and antioxidant capacity. Particle size reduction significantly modified the distribution of nutrients and bioactive compounds, increasing protein, ash, moisture, and several key minerals, as well as antioxidant potential. Finer flours exhibited higher water activity, darker coloration, and greater redness and yellowness while medium-size particles displayed the highest oil-holding capacity. Overall, black quinoa flour obtained from "destrío" grains emerges as a valuable-added ingredient with promising applications in the development of sustainable food formulations, thus contributing to circular economy principles and improving the eco-efficiency of the agro-food sector.

1. Introduction

Eco-efficiency is a strategy aimed at increasing productivity by reducing the use of natural resources and waste. In the food sector, one important aspect of this approach is to recover and utilize industrial co-products, which can enhance efficiency and sustainability (Ribeiro et al., 2022). Considering the growing environmental impact of food waste-estimated at nearly 59 million tons in Europe alone (European Commission, 2024) the transformation of such co-products into functional ingredients represents a practical way to reduce waste while using circular economy practices (Roy et al., 2023).

In this context, one of the main sources of co-products and waste in the food industry and agriculture are the crops that do not fulfill commercial quality standards. In quinoa production, this includes small, immature, broken or split, irregularly shaped or mechanically damaged

grains that are discarded (representing around 10 % of the total production) despite being nutritionally suitable for consumption. In Spain, these grains are commonly known as "destrío", and their valorization aligns with sustainable production goals, as they maintain their nutritional value, technological properties and bioactive compounds than can be used for food innovation. In 2024, Spain produced around 1800 tons of quinoa, making it the leading producer in Europe and accounting for practically 100 % of EU production (IndexBox, 2025). There are no separate official public data quantifying the area, production, or economic value for black quinoa alone. Considering these production data and the market economic value of quinoa in general (€10/kg), the value of this "destrío" would be approximately €1.8 million. It should be noted that if only black quinoa were considered, its market price is even higher than that of white quinoa.

Quinoa (*Chenopodium quinoa* Willd), a pseudocereal indigenous to

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the Andean region, is widely recognized for its balanced nutrient profile, containing high-quality proteins, unsaturated lipids, dietary fiber, essential minerals, and bioactive phytochemicals (Fernández-López et al., 2024; Hernández-Ledesma, 2019; Tang et al., 2015). Its gluten-free nature and functional properties have positioned quinoa as a relevant ingredient in health-oriented and celiac diets (Ayoub Casalvira et al., 2024; Guo et al., 2025; Pellegrini et al., 2018). The milling process greatly influences quinoa flour's physical, nutritional, and techno-functional properties, as it alters the exposure of nutrients, pigments, and bioactive compounds. Particle size reduction can modify moisture retention, color, hydration capacity, and antioxidant activity (Aranibar et al., 2018; Tang et al., 2015). However, no previous studies have examined how controlled particle-size milling affects the chemical composition and physicochemical behavior of flours derived specifically from discarded quinoa grains.

Therefore, this work aims to assess the impact of particle size reduction on the chemical composition, mineral content, physicochemical and techno-functional properties as well as on the antioxidant capacity of flour produced from black quinoa "destrío" grains. This research contributes to the valorization of agricultural co-products through a sustainable and non-chemical processing approach, in line with the circular economy objectives within the agri-food sector.

2. Materials and methods

2.1. Quinoa flour

"Destrió" grains from the industrial processing of black quinoa (cultivated in León, Spain) were provided by the same supplier (Alberto González, León, Spain) from 3 different commercial batches. Firstly, the grains were washed with distilled water (ratio 1:1) for 30 min at room temperature. After washing, they were drained and oven-dried at 55 °C for 48 h. Subsequently, they were ground (electric blade grinder, Black Decker, Lérida, Spain) and passed through sieves (0.70, 0.42, 0.21 and 0.10 mm mesh) to obtain four quinoa flours with different particle sizes as follows: HQF, highest quinoa flour (0.70 mm > ϕ > 0.42 mm); MHQF, Medium-high quinoa flour (0.42 mm > ϕ > 0.21 mm); MLQF, Medium-low quinoa flour (0.21 mm > ϕ > 0.10 mm) and LQF, lowest quinoa flour (ϕ < 0.10 mm) (Fig. 1). Finally, quinoa flours were stored in vacuum packaging until their analysis.

2.2. Chemical composition

Moisture (AOAC 925.45), protein (AOAC 981.10), fat (AOAC 991.36), ash (AOAC 923.03), and total dietary fiber, TDF (AOAC 985.29) were determined in triplicate according to the AOAC methods (Official Methods of Analysis, 18th Edition, Association of Official Analytical Chemists, 2006). Mineral composition was determined using the same method described in our previous work (Muñoz-Tebar et al., 2024). The measurements were performed in triplicate, and the mineral content was expressed as mg/100 g of flour.

2.3. Physicochemical properties

The pH value was measured using a pH-meter GLP21 (Crison Barcelona, Spain) with the samples diluted 1:10 in deionized water, and CIELAB coordinates were determined with a CM-700 Minolta spectrophotometer (Minolta, Osaka, Japan). Water activity (*a_w*) was measured in a Novasina TH-500 (Novasina, Axair Ltd., Pfaeffikon, Switzerland) at room temperature. All the measurements were performed in triplicate.

2.4. Techno-functional properties

The water-holding capacity (WHC), oil-holding capacity (OHC), and swelling capacity (SWC) were evaluated in triplicate using the same method described by Muñoz-Bas et al. (2023). For WHC and OHC, 10 mL of ultrapure water or 5 g of sunflower oil were added to centrifuge tubes containing 0.5 g of quinoa flour. The tubes were kept at 25 °C for 18 h and then centrifuged at 1200 g for 20 min (Nahita Model 2652, Alicante, Spain). The supernatant was removed, and the pellet was weighed (Eqs. (1) and 2).

$$WHC \text{ (g water/g sample)} = \frac{WTP - WT - WS}{WS} \quad (1)$$

$$OHC \text{ (g oil/g sample)} = \frac{WTP - WT - WS}{WS} \quad (2)$$

Being: WTP- the weight of the tube and pellet after centrifugation (g); WT- tube weight (g); WS- sample weight (g)

For SWC, 0.2 g of sample was placed in a 10-mL graduated tube, and the initial volume was recorded (V0). Then, 5 mL of ultrapure water was added, the mixture was stirred and left at room temperature for 24 h. The final volume of the hydrated sample (V1) was then measured (Eq. (3)).

$$SWC \text{ (mL/g sample)} = \frac{V1 - V0}{WS} \quad (3)$$

The results were expressed as grams of water held (WHC) or oil held (OHC) by 1 g of quinoa flour and as mL per gram of quinoa flour in the case of SWC.

2.5. Antioxidant activity

The antioxidant properties of the flours were assessed in triplicate using the DPPH (2,2-diphenyl-1-picrylhydrazyl), ABTS (2,2'-azino-bis(3-ethylbenzothiazoline-6-sulfonic acid)) and FRAP (ferric ion reducing antioxidant potential) antioxidant assays. DPPH and ABTS were carried out following the methods described by Brand-Williams et al. (1995) and Gullón et al. (2015), respectively. FRAP was performed according to the method described by Oyaizu (1986). Absorbance values were measured on a spectrophotometer at 517 nm, 734 nm and 700 nm for DPPH, ABTS and FRAP, respectively. Trolox was used as standard and the results were expressed as μ g Trolox equivalents (TE)/ g flour in

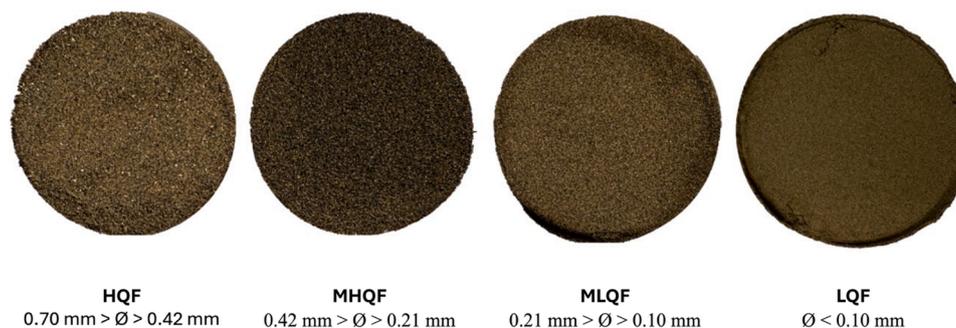


Fig. 1. Black quinoa co-products (*Chenopodium quinoa*) flours with different particle sizes.

DPPH and as mg TE/g flour in ABTS and FRAP.

2.6. Statistical analysis

Statistical analysis of data ($n = 3$) was performed using SPSS (IBM SPSS Statistics version 26). ANOVA (one way) was calculated using a confidence level of 95 % to determine any significant differences ($p < 0.05$) and Tukey test was carried out to determine the differences between the different particle sizes of quinoa flour.

3. Results and discussion

After grinding the “destrío” quinoa grains and sifting the flour, the yield obtained according to the size of the grind was: 40 % HQF, 27 % MHQF, 19 % MLQF, and 14 % LQF.

3.1. Chemical composition

Table 1 summarizes the chemical composition of quinoa flour derived from “destrío” grains with varying particle sizes.

All flours exhibited higher protein and ash contents than those previously reported for black quinoa flours by Pellegrini et al. (2018) (12.44 % and 2.37 %, respectively) and Ramos-Pacheco et al. (2024) (12.41 % and 2.20 %, respectively). Similarly, the values obtained in this study were greater than those reported for white quinoa varieties in the studies conducted by Dularia et al. (2024) and Otoo and Aryee (2025). However, the moisture and fat contents were markedly lower than those documented in the literature for both black and white varieties, which ranged from 5.27 % to 9.67 % for moisture and from 5.31 % to 7.30 % for fat (Dularia et al., 2024; Otoo & Aryee, 2025; Pellegrini et al., 2018; Ramos-Pacheco et al., 2024). Genetic and environmental effects on nutritional profiles of quinoa varieties have also been reported by these authors.

The anatomical characteristics of “destrío” quinoa grains could explain the nutritional composition observed in the flours. Proteins and lipids are predominantly concentrated in the germ, whereas dietary fiber is mainly located in the bran layers (Fernández-López et al., 2024). Since quinoa “destrío” grains are characterized by being smaller and having a higher proportion of husk and pericarp (also known as bran) and a lower proportion of germ than commercial quinoa grains, flours derived from them inherently present higher levels of fiber and ash (Ge et al., 2024). Additionally, the relatively stable fat content across particle sizes is consistent with the limited contribution of the germ in these “destrío” grains.

As Table 1 shows, particle size reduction did not exert a significant effect on dietary fiber or lipid contents ($p > 0.05$), which remained comparable across all fractions. As previously stated, quinoa “destrío”

Table 1

Nutritional composition of quinoa flour with different particle sizes (mean \pm sd).

Parameter (dry basis)	HQF	MHQF	MLQF	LQF
% Protein	17.08 \pm 0.81 ^{ab}	18.20 \pm 0.02 ^a	17.07 \pm 0.03 ^b	18.07 \pm 0.02 ^{ab}
% Fat	4.76 \pm 0.77 ^a	5.35 \pm 0.46 ^a	4.28 \pm 0.07 ^a	5.54 \pm 0.79 ^a
% Moisture	2.60 \pm 0.71 ^b	3.49 \pm 0.02 ^{ab}	3.80 \pm 0.13 ^{ab}	3.89 \pm 0.11 ^a
% Ash	7.49 \pm 0.30 ^c	9.25 \pm 0.27 ^b	9.34 \pm 0.18 ^b	12.68 \pm 0.22 ^a
% Total Dietary fiber (TDF)	54.57 \pm 1.24 ^a	63.13 \pm 4.90 ^a	63.20 \pm 3.40 ^a	60.48 \pm 1.71 ^a

^{a-c} Different letters between columns means significant differences ($p < 0.05$) due to quinoa flour with different particle sizes. HQF, highest quinoa flour (0.70 mm $> \theta > 0.42$ mm); MHQF, Medium-high quinoa flour (0.42 mm $> \theta > 0.21$ mm); MLQF, Medium-low quinoa flour (0.21 mm $> \theta > 0.10$ mm) and LQF, lowest quinoa flour ($\theta < 0.10$ mm).

grains contained a higher proportion of bran. The milling process leads to the mechanical disruption of cellular structures, which reduces the physical inaccessibility of starch (Chen et al., 2024; Zhong et al., 2025). Consequently, the higher dietary fiber values observed are more plausibly associated with concentration effects and greater analytical recovery of fiber-rich fractions, particularly bran, which contains a higher dietary fiber content than the germ, as reported by Ray et al. (2021). On the other hand, moisture, protein, and ash contents significantly increased ($p < 0.05$) as particle size decreased, reaching the highest values in the finest flour ($\theta < 0.10$ mm) except for the protein that was in MHQF flour (18.20 %). The observed increase in moisture content (from 2.60 % in the coarsest fraction to 3.89 % in the finest fraction) could be attributed to the significant increase in the material's specific surface area upon grinding that can lead to a higher moisture content (Meng et al., 2018). Moisture content is a critical parameter in flours, as it influences both the chemical and physical properties of the final food products and their storage stability (Nabil et al., 2020). In this regard, all flours exhibited moisture values below the threshold established for safe storage (8–10 %; (Nabil et al., 2020) and were substantially lower than the 12 % limit generally recommended to ensure the stability and safety of co-products and by-products (Socas-Rodríguez et al., 2021). These results suggest that reducing flour particle size would not affect its preservation in terms of moisture content.

An increase in moisture associated with finer particle sizes has previously been observed by Ahmed et al. (2019) in quinoa flour (30 and 50-mesh fractions). Similarly, Dhen et al. (2016) and Lucas-González et al. (2017) reported higher moisture contents when they reduce the particle size in soy and persimmon flours, respectively. In the present study, protein content increased from 17.08 % to 18.20 % in the finest flour ($\theta < 0.10$ mm). Moreover, the cell-wall material from the breakdown of endosperm during milling and subsequent sieving may be the reason why higher ash values were obtained in the smaller particle sizes compared to coarser flour (12.68 % vs. 7.49 %), consistent with the findings of Ahmed et al. (2019) regarding the influence of particle size on quinoa flour dispersions.

Furthermore, black quinoa flour derived from “destrío” grains used in the present study exhibited a better nutritional profile—characterized by higher protein, lipid and dietary fiber—compared with cereals commonly employed in the food industry such as barley, rye, oat, millet, triticale and sorghum (Torbica et al., 2021).

3.2. Mineral composition

The analysis of mineral composition of black quinoa flour obtained from “destrío” grains revealed that the main macrominerals were potassium (K), followed by calcium (Ca), magnesium (Mg), and phosphorus (P), while the most abundant microminerals were iron (Fe), manganese (Mn), and zinc (Zn) (Table 2).

Studies on the evaluation of the mineral profile of quinoa (both grain and flour) are very limited. In this sense, Otoo and Aryee (2025) evaluated the mineral content of flour obtained from white quinoa, reporting lower contents of Ca, K, Mg, Na, Cu, and Zn and a higher content of P compared to the values obtained in the present study. On the other hand, Diaz-Valencia et al. (2018) analyzed black quinoa grains and found substantially lower levels of most minerals except phosphorus and zinc, whose values were higher than those determined in the present study.

Sieving the flour led to a significant increase ($p < 0.05$) in the concentration of all minerals as particle size decreased, except for copper and zinc, since no significant differences were detected among particle sizes (Table 2). This increase is consistent with the behavior observed in ash (Table 1), as the degradation of the endosperm during milling and subsequent sieving releases the mineral-rich wall material. Given that milling may be exposing or concentrating these mineral-containing fractions, it was expected to have higher mineral values as particle size was reduced.

Scientific studies about how particle sizes affect the mineral

Table 2

Mineral profile (mg/100 g dw) of quinoa flour with different particle sizes (mean \pm sd).

Parameter	HQF	MHQF	MLQF	LQF
Ca	930.75 \pm 7.16 ^d	1059.14 \pm 34.26 ^c	1299.75 \pm 17.85 ^b	2015.64 \pm 14.81 ^a
Cu	0.92 \pm 0.02 ^a	0.94 \pm 0.02 ^a	0.95 \pm 0.05 ^a	0.94 \pm 0.00 ^a
Fe	19.04 \pm 1.15 ^b	19.74 \pm 0.23 ^b	21.37 \pm 1.73 ^b	47.90 \pm 0.91 ^a
K	1783.33 \pm 49.44 ^c	2090.86 \pm 117.91 ^{ab}	2194.01 \pm 10.71 ^a	2020.62 \pm 13.75 ^b
Mg	468.91 \pm 14.34 ^c	512.10 \pm 6.54 ^b	497.91 \pm 5.91 ^{bc}	552.14 \pm 12.18 ^a
Mn	18.21 \pm 0.37 ^d	21.53 \pm 0.65 ^c	22.53 \pm 0.14 ^b	23.90 \pm 0.11 ^a
Na	39.70 \pm 0.45 ^b	44.41 \pm 2.09 ^a	44.05 \pm 2.19 ^{ab}	43.65 \pm 1.27 ^{ab}
P	362.91 \pm 18.56 ^{ab}	366.78 \pm 39.07 ^{ab}	326.40 \pm 1.63 ^b	395.81 \pm 3.60 ^a
Zn	4.88 \pm 0.73 ^a	3.87 \pm 0.52 ^a	4.73 \pm 0.23 ^a	4.85 \pm 0.34 ^a

dw: dry weight; ^{a-d} Different letters between rows means significant differences ($p < 0.05$) due to quinoa flour with different particle sizes. HQF, highest quinoa flour (0.70 mm $> \phi > 0.42$ mm); MHQF, Medium-high quinoa flour (0.42 mm $> \phi > 0.21$ mm); MLQF, Medium-low quinoa flour (0.21 mm $> \phi > 0.10$ mm) and LQF, lowest quinoa flour ($\phi < 0.10$ mm).

composition of flours remains very limited, and, to our knowledge, no prior studies have been found that carry out these analyses on black quinoa flours. In fact, the only available data found in the literature that analyze this come from two recent works conducted by our group, focused on date seed flour and mushroom co-product flours, both of which reported a higher mineral content when the particle size was reduced (Bermúdez-Gómez et al., 2024; Muñoz-Tebar et al., 2024).

The highest calcium content was found in the finest flour (2015.64 mg/100 g), which was twice higher than the coarsest flour (930.75 mg/100 g). Remarkably, the calcium content of the flours would even exceed the Dietary Reference Value (DRV) established by the EFSA (EFSA, 2017) for adults over 25 years (950 mg/day). Likewise, the highest potassium content was achieved in MLQF flour (0.21 mm $> \phi > 0.10$ mm) with a value of 2194.01 mg/100, which would represent 63 % of the DRV (3500 mg/day). Therefore, black quinoa flour obtained from "destrío" grains could be a valuable source of both calcium and potassium for the formulation of fortified foods. On the other hand, the sodium content observed in all flours demonstrate that they could be used in the development of low-sodium foods, in line with the recommendations of the World Health Organization on reducing sodium intake to lower the risk of cardiovascular or coronary heart disease in adults (World Health Organization, 2012). Another micronutrient of great importance is iron, reaching the highest content in the finest flour, being 2.5-fold higher than the content of the HQF flour (47.90 vs. 19.04 mg/100 g).

Finally, when compared with other cereals and pseudocereals, the mineral contents (Na, K, Mg, Ca, Mn, and Fe) determined in this study were consistently higher than those reported for barley, triticale, millet, oat, sorghum, wheat and amaranth (Mehraj Allai et al., 2022; Torbica et al., 2021). It should also be noted that the bioavailability of minerals in plant materials is relatively low due to certain molecules, such as phytates or phenols, forming complexes (Ojo, 2020). Sánchez-García et al. (2023) reported mineral bioaccessibility values of 50 % for Mg, 65 % for Ca, and 67 % for Fe in black quinoa flour.

3.3. Physicochemical properties

The physicochemical properties of black quinoa flour obtained from "destrío" grains are presented in Table 3.

Overall, the flours exhibited slightly higher pH values compared to those reported by Pellegrini et al. (2018) for black quinoa flour. In contrast, the water activity (aw) values were comparable to those described by the same author, but higher than the value reported by

Table 3

Physicochemical properties of quinoa flour with different particle sizes (mean \pm sd).

Parameter	HQF	MHQF	MLQF	LQF
pH	6.37 \pm 0.11 ^b	7.03 \pm 0.04 ^a	7.10 \pm 0.01 ^a	7.08 \pm 0.01 ^a
aw	0.30 \pm 0.00 ^c	0.39 \pm 0.00 ^b	0.39 \pm 0.01 ^b	0.41 \pm 0.00 ^a
L*	41.08 \pm 0.53 ^a	30.95 \pm 0.19 ^d	35.53 \pm 0.08 ^c	40.00 \pm 0.07 ^b
a*	3.86 \pm 0.05 ^b	3.33 \pm 0.15 ^c	3.72 \pm 0.04 ^b	4.12 \pm 0.04 ^a
b*	11.15 \pm 0.35 ^b	8.00 \pm 0.23 ^d	9.74 \pm 0.11 ^c	12.12 \pm 0.38 ^a
C*	11.80 \pm 0.35 ^b	8.66 \pm 0.28 ^d	10.42 \pm 0.10 ^c	12.80 \pm 0.37 ^a
h°	70.89 \pm 0.05 ^b	67.39 \pm 0.41 ^d	69.23 \pm 0.23 ^c	71.21 \pm 0.38 ^a

^{a-d} Different letters between columns means significant differences ($p < 0.05$) due to quinoa flour with different particle sizes. HQF, highest quinoa flour (0.70 mm $> \phi > 0.42$ mm); MHQF, Medium-high quinoa flour (0.42 mm $> \phi > 0.21$ mm); MLQF, Medium-low quinoa flour (0.21 mm $> \phi > 0.10$ mm) and LQF, lowest quinoa flour ($\phi < 0.10$ mm).

Ramos-Pacheco et al. (2024) for flour from the black Collana quinoa variety (0.11).

Regarding color parameters, lightness (L*) and hue angle (h°) values observed in this study were lower than those reported in other studies on black quinoa flour (69.94 and 77.73, respectively). However, coordinates a*, b*, and chroma (C*) were higher than the values previously reported in the literature (Pellegrini et al., 2018; Ramos-Pacheco et al., 2024).

Regarding particle size, the results presented in Table 3 indicate that size reduction had a significant impact on all physicochemical parameters ($p < 0.05$). The pH values increased from 6.37 to 7.10 and water activity rose from 0.30 to 0.41 in the flour with the smallest particle size. The increase in aw followed the same trend observed for moisture content (Table 1). Despite these variations, all flours exhibited aw values within the recommended thresholds for safe storage, suggesting a low risk of deterioration by microbial growth as well as enzymatic or non-enzymatic reactions.

Similar patterns have been reported in other plant-based flours. For instance, particle size reduction has been associated with increases in aw in banana flour (from 0.40 to 0.42; Savlak, 2016), cocoa shell flour (increasing from 0.47 to 0.50; Botella-Martínez et al., 2021), and mushroom co-products flour (pH from 6.16 to 6.18 and aw from 0.38 to 0.42; Bermúdez-Gómez et al., 2024). Likewise, our recent study on date seed flour demonstrated a similar behavior, with finer flour exhibiting the highest aw value (Muñoz-Tebar et al., 2024).

Concerning color, sieving had a significant influence by causing a decrease in brightness with the reduction in particle size being more pronounced in the medium particle sizes (MHQF and MLQF). Likewise, coordinates a* and b* increased in the finest flour ($\phi < 10$ mm) compared to the flour with the highest particle size (0.70 mm $> \phi > 0.42$ mm), while in the medium sizes the values were lower than those of the coarsest flour. For the coordinate a*, the highest value was recorded in the LQF flour (4.12), while the MHQF had the lowest value (3.33). A similar pattern was observed for coordinate b* increasing from 11.15 to 12.80, with medium-low particle sizes (0.21 mm $> \phi < 0.10$ mm) having the lowest values. These findings suggest that flours with finer particles displayed more reddish and yellowish compared to larger particles. The reduction in lightness (L*) and the slight increase in redness (a*) and yellowness (b*) in the finest flour can be attributed to the release and oxidation of phenolic pigments during fine milling. The pigments in black quinoa are mainly located in the seed's outer layers, and their exposure to oxygen and heat from mechanical friction promotes browning and darkening of the flour (Ahmed, Taher, Mulla, Al-Hazza et al., 2016; Botella-Martínez et al., 2021).

Consistent with this, increases in a* and b* values have also been reported in cocoa shell and date seed flours due to particle size reduction (Botella-Martínez et al., 2021; Muñoz-Tebar et al., 2024). On the other hand, chroma (C*) and hue angle (h°) followed a similar behaviour than coordinate b*. C* increased significantly ($p < 0.05$) from 11.80 to 12.80,

and h° increased from 70.89 to 71.41 in the finest flour ($\phi < 0.10$ mm). As shown in Table 3, all samples exhibited hue values within the orange range (60–90°), shifting towards a more orange-reddish as particle size decreased from 0.70 to <10 mm (Scalisi et al., 2022).

3.4. Techno-functional properties

The techno-functional properties of black quinoa flour are presented in Table 4 as water-holding capacity (WHC), oil-holding capacity (OHC), and swelling capacity (SWC).

The WHC and OHC values obtained were considerably higher than those reported by Otoo and Aryee (2025) for white quinoa flour dispersions, which showed 1.12 g/g for WHC and 0.89 g/g for OHC. As shown in Table 4, particle size reduction did not significantly influence WHC or SWC ($p > 0.05$); however, oil-holding capacity was significantly increased in medium particle sizes (MHQF and MLQF), obtaining the same value in both flours. The lowest OHC was found in the finest flour, whereas the highest values were recorded in samples with particle sizes between 0.42 mm and $\phi > 0.10$ mm, reaching 1.73–1.74 g oil/g flour. The OHC of a food ingredient (flour, fiber, protein concentrates) is directly related to the hydrophobic fraction of its components, both proteins and insoluble fiber, although through different and complementary mechanisms (Wittmüss et al., 2024). On the one hand, the milling process can increase the exposure of the hydrophobic areas of proteins, facilitating their accessibility and thus increasing OHC. On the other hand, the effect of insoluble fiber is more physical than chemical because it acts by forming a rigid three-dimensional network in which the oil is retained not by a strong molecular bond, but by physical retention and surface affinity (de Oliveira et al., 2025). In the case of fine milling, there is a decrease in OHC due to a decrease in porosity.

Improvements in oil-holding capacity with decreasing particle size have also been reported in other plant-based flours. Ahmed et al. (2016), for instance, observed higher OHC values when lentil flour particle size was reduced from 210 to 105 μ m, followed by a decline in the finest flour, a pattern consistent with the present findings. Similarly, Lucas-González et al. (2017) recorded increases in OHC values when the particle size of in persimmon flour was reduced (from > 0.701 to < 0.210 mm), with values comparable to those obtained in our study. Likewise, Bermúdez-Gómez et al. (2024) reported an increase in OHC in flours obtained from mushroom co-products, reaching a value of 4.78 g/g in the finest flour (< 0.180 mm).

The OHC values obtained suggest that flour from quinoa "destrío" grains could be used in fried products, reducing the sensation of greasiness (Lucas-González et al., 2017).

Regarding hydration properties, the WHC and SWC values obtained ranged from 2.12 to 3.80 g water/g flour and from 1.66 to 2.39 mL water/g flour, respectively. It has been reported that reducing particle size exposes more hydrophilic groups, contact area and sites for water interaction (Yang et al., 2024). On the contrary, this breakage would promote the structural disorganization of the main constituents (fibers

Table 4

Techno-functional properties of quinoa flour with different particle sizes (mean \pm sd).

Parameter	HQF	MHQF	MLQF	LQF
WHC (g water/g sample)	3.80 \pm 1.01 ^a	3.61 \pm 0.08 ^a	3.40 \pm 0.09 ^a	2.12 \pm 1.83 ^a
OHC (g oil/g sample)	1.58 \pm 0.07 ^b	1.73 \pm 0.03 ^a	1.74 \pm 0.16 ^a	1.46 \pm 0.09 ^b
SWC (ml water/g sample)	2.00 \pm 0.60 ^a	2.10 \pm 0.33 ^a	2.39 \pm 0.32 ^a	1.66 \pm 0.29 ^a

^{a-b} Different letters between columns means significant differences ($p < 0.05$) due to quinoa flour with different particle sizes. HQF, highest quinoa flour (0.70 mm $> \phi > 0.42$ mm); MHQF, Medium-high quinoa flour (0.42 mm $> \phi > 0.21$ mm); MLQF, Medium-low quinoa flour (0.21 mm $> \phi > 0.10$ mm) and LQF, lowest quinoa flour ($\phi < 0.10$ mm).

and starches) which would damage their ability to absorb and retain water. Li et al. (2025) reported that particle size of wheat bran dietary fiber did not significantly influence WHC values, which is consistent with our results. Additionally, the relatively low WHC values indicate that the flours present a low risk of microbial contamination and spoilage, an important property in products designed for long-term storage.

3.5. Antioxidant activity

The results presented in Table 5 show that the antioxidant capacity of the flour obtained in this study was lower than the values reported by Pellegrini et al. (2018) for flour obtained from Bolivian black quinoa. These differences could be linked to the variety, growth environment and cultivation conditions, as well as the extraction methods and solvents used (Guo et al., 2025b).

The reduction in particle size had a significant impact on antioxidant activity ($p < 0.05$), being all flours different from each other (Table 5). In the DPPH assay, MHQF displayed the highest ability to scavenge DPPH radicals (131.11 \pm 22.51 μ g TE/g), while MLQF showed the lowest activity. This difference may be linked to how well the phenolic compounds are retained during processing, since these metabolites are well-known to play a significant role in neutralizing DPPH radicals (Tang et al., 2015). In addition, the high mineral content, along with the increase in protein (Table 1) suggests a greater exposure of the highly reactive cellular components. This would explain the highest DPPH activity due to a possible better extractability and availability of phenolic compounds and other radical scavengers bound within the cell walls, likely due to the increased surface area (Ahmed et al., 2019; Chen et al., 2022).

In contrast, no significant differences were observed among samples in the ABTS, which suggests that the compounds responsible for quenching ABTS $\bullet+$ radicals, such as flavonoids and saponins, remained relatively stable across the different flours (Chen et al., 2022). However, the FRAP assay showed significant differences, with LQF exhibiting the highest reducing power (1.06 \pm 0.06 mg TE/g). This can be linked to a higher concentration of electron-donating compounds, including phenolic acids or Maillard-derived products formed during drying or milling (Pellegrini et al., 2018; Vilcacundo & Hernández-Ledesma, 2017). The lower FRAP value of MLQF could indicate a loss or transformation of such compounds. A similar effect in the antioxidant capacity has been previously reported by Savlak et al. (2016) when they reduced the particle size of unripe banana flour from 700 to < 212 μ m.

Overall, these results prove that the antioxidant potential of black quinoa flour from "destrío" grains is highly dependent on the phenolic retention and Maillard-derived compound formation, both influenced by the particle size reduction and processing conditions.

Table 5

Antioxidant capacity of quinoa flour with different particle sizes (mean \pm sd).

Parameter	HQF	MHQF	MLQF	LQF
DPPH (μ g TE/g)	98.25 \pm 15.31 ^a	131.11 \pm 22.51 ^a	43.35 \pm 26.13 ^b	93.14 \pm 17.23 ^a
ABTS (mg TE/g)	0.83 \pm 0.09 ^a	0.58 \pm 0.03 ^a	0.81 \pm 0.09 ^a	0.79 \pm 0.11 ^a
FRAP (mg TE/g)	0.40 \pm 0.06 ^c	0.90 \pm 0.08 ^b	0.14 \pm 0.03 ^d	1.06 \pm 0.06 ^a

^{a-c} Different letters between rows means significant differences ($p < 0.05$) due to quinoa flour with different particle sizes. HQF, highest quinoa flour (0.70 mm $> \phi > 0.42$ mm); MHQF, Medium-high quinoa flour (0.42 mm $> \phi > 0.21$ mm); MLQF, Medium-low quinoa flour (0.21 mm $> \phi > 0.10$ mm) and LQF, lowest quinoa flour ($\phi < 0.10$ mm).

4. Conclusions and perspectives

The present study demonstrates that flour produced from black quinoa "destrío" grains represents a valuable and sustainable potential ingredient for novel food formulations. The particle size reduction enhanced the compositional and functional properties of the flour, highlighting the potential of milling as a strategy for valorizing quinoa co-products within circular economy frameworks. The results suggest that these flours produced from "destrío" grains could be a good raw material for sustainable food applications such as bakery products (bread, cookies, biscuits, etc.), snacks or other cereal-based products (pasta, muesli, granola, etc.). All fractions are suitable for dietary fiber fortification of foods. Medium particle size fractions (MHQF and MLQF) could also be incorporated into meat mixtures or even plant-based mixtures due to their greater OHC. MHQF would also be the fraction of choice in the meat industry due to its highest antioxidant activity. Future research should focus on evaluating the digestibility, bioavailability, and sensory acceptability of products formulated with "destrío" quinoa flour, to support its industrial scaling and consumer acceptance.

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Ethical statement not necessary

This work does not imply studies in animals or humans.

CRediT authorship contribution statement

Nuria Muñoz-Tebar: Writing – original draft, Validation, Formal analysis. **Clara Muñoz-Bas:** Writing – original draft, Methodology, Investigation. **Manuel Viuda-Martos:** Writing – review & editing, Validation, Data curation, Conceptualization. **Estrella Sayas-Barberá:** Writing – review & editing, Supervision, Funding acquisition. **José Manuel Lorenzo:** Writing – review & editing, Supervision, Resources. **José Ángel Pérez-Álvarez:** Writing – review & editing, Validation, Supervision, Funding acquisition, Conceptualization. **Juana Fernández-López:** Writing – review & editing, Visualization, Supervision, Formal analysis, Data curation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

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