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Functional and Pasting Properties of Starch from Six Peruvian Quinoa (*Chenopodium quinoa* Willd.) Cultivars with Different Seed Color

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Abstract

Quinoa (*Chenopodium quinoa* Willd.) is an Andean pseudocereal that has received increasing attention from consumers in recent years. Starch is the main constituent of quinoa. In this study, we evaluated the color, amylose content, relative crystallinity, functional properties (water-absorption index (WAI), water-solubility index (WSI) and swelling power (SP)) and pasting properties of starch extracted by an alkaline method from the seeds of six Peruvian quinoa cultivars of different colors (white: INIA 431 "Altiplano" (WAQ), Salcedo INIA (WSQ), Kancolla (WKQ), Illpa INIA (WIQ), black: INIA 420 "Negra Collana" (BNQ), and red: INIA 415 "Roja Pasankalla" (RPQ)). Starches from light cultivars were found to have the highest reflectance (L* value), while red and black cultivars had the highest a* and b* values. Starch amylose content determined by a colorimetric iodine assay was similar among cultivars (25.45 ± 4.43%), as well as relative crystallinity and functional properties. Starches from clear cultivars had the highest peak viscosity (PV). BNQ had the highest pasting temperature (PT) (62.06 °C), but the lowest PV, trough viscosity (TV), final viscosity (FV) and setback viscosity (SV). RPQ had the highest TV. The different pasting properties of starches would allow them to be used in different applications.

Keywords

Amylose, Chenopodium, Pasting properties, Starch, X-ray diffraction

Introduction

Quinoa is a pseudocereal of the genus Chenopodium, native to the area around the Altiplano plateau between Peru and Bolivia and currently cultivated from sea level to 4000 m above sea level [1]. The seeds of this Andean pseudocereal have received the attention of consumers and industry worldwide for their nutritional properties and commercial value [2]. The increase in demand has also generated the development of new cultivars with particular characteristics that differentiate them from the rest by size, seed color and nutritional composition. The composition of the seeds depends on agronomic factors as well as on the genotype and the sowing season [3]. Food products developed from quinoa seeds include fermented beverages, cookies, pasta, noodles and bakery products [4]. The development of beverages from the leaves of the plant [5], emulsions [6] and biodegradable films [7] made from the starch in the seeds has also been studied.

Starch is the main component of quinoa seeds, representing 47 - 60% of the dry weight of the milled seeds [8]. The size of its granules (0.46 - 5.56 μm) is tiny compared to that of Andean tubers such as potato (4.17 - 120.23 μm) [9] and *Ullucus tuberosus* (4.45 - 24.9 μm) [10]. Differences in the size and structure of the quinoa starch granule affect the distribution of moisture during heating of bakery products, causing the doughs to behave differently [11]. The functional properties

(WAI, WSI, and SP) of starches are important for the development of foods based on flours and starches [12]. The pasting properties reflect the viscosity behavior of a paste that is subjected to heating and shear stress and are used to select the application of the flour or starch. The proximal composition of the flour has a considerable effect on the pasting properties. With isolated starches, it is the complexes formed by amylose that play the most important role in the shear strength of the pastes and the resistance of the swollen starch granules [13]. It was initially reported that quinoa starches had very different pasting properties compared to cereals such as wheat [14]; however, the pasting properties themselves also vary among different quinoa cultivar [15] with reported PT ranging from 51.3 - 65.8 °C and peak viscosities from 313 - 474 RVU (Rapid Visco unit). In another study, quinoa starches exhibited PT of approximately 72.6 °C, peak viscosities between 2983 and 3551 cP, and SP values ranging from 21.8 - 28.1 g/g [9], highlighting the influence of genotype and growing conditions on these functional characteristics.

Previously, the nutritional composition [8] and lipid profile [16] of some Peruvian quinoa cultivars of different colors were studied, as well as the pasting properties of some mixtures of flours of white Peruvian quinoa cultivars [17], but only rarely were the functional and pasting properties of the starches of red or black Peruvian quinoa cultivars studied. The aim of this work was to determine the amylose content and the functional and pasting properties of starch extracted from the seeds of six Peruvian cultivars of different colors obtained from a germplasm bank.

Materials and Methods

Materials

The samples of the six quinoa seed cultivars were obtained from the germplasm of the Instituto Nacional de Investigación Agraria (INIA). The cultivars were WAQ, WSQ, WKQ, WIQ, BNQ, and RPQ. WAQ, WSQ, WKQ, and WIQ seeds had a white episperm, while RPQ seeds were red and BNQ seeds were black [1]. Although the present study focused on starch characterization, additional compositional data for these cultivars (e.g., protein, lipid, fiber, and ash contents) have been reported previously: cultivar-level information for WSQ, RPQ, and BNQ is available in Diaz-Valencia et al. [8], and seed composition for all six cultivars is described in Apaza et al. [1].

The seeds were kept in sealed polyethylene bags under refrigeration at 5 °C until the time of analysis. The chemicals used for the analysis were reagent grade (ACS).

Starch extraction and color evaluation

Starch from the quinoa samples was extracted according to the method described by Araujo-Farro et al. [7] with some modifications. The previously washed quinoa grains were ground in a blender and the crushed material passed through 80 mesh (177 µm) and 325 mesh (44 µm) sieves. The material retained on the sieves was washed with water and the procedure was repeated five times.

The starch in the filtered material was isolated by centrifugation (5000 g × 15 min). The starch precipitate was re-suspended in 50 mL of distilled water, centrifuged under the same conditions, and then the dark-colored top layer containing protein and fiber and other impurities was removed with a spatula. This procedure was repeated 5 times by removing the top layer after each centrifugation. The starch obtained was re-suspended in a 50 mL of NaOH solution (0.05 mol/L, pH = 10.5). It was centrifuged again to remove the top layer and then the starch was re-suspended in a 50 mL of HCl solution (1 mol/L). After another centrifugation, the top layer was removed. The purified starch was dried in a heating oven (Binder GmbH, Germany) at 37 °C for 12 h and immediately ground with a mortar and pestle and then sieved with a 60 mesh (250 µm) screen. The moisture content of the purified starches was determined using a halogen moisture analyzer (MX-50, A&D Co. Ltd., Tokyo, Japan) prior to pasting and color evaluation.

The color was measured by the CIE lab scale (L* a* b*) using a colorimeter (Chroma Meter CR-400, Konika Minolta, Japan). Measurements were made in triplicate.

Amylose content

The starch samples were treated with 90% dimethylsulfoxide ($(CH_3)_2SO$) in a ratio of 1:50 (w/v) and subjected to agitation in a boiling water bath for 1 h to promote solubilization prior to iodine-binding analysis [18]. After cooling, the starch was precipitated with three volumes of absolute ethanol and separated by centrifugation (1600 g × 15 min). The precipitate was dispersed with absolute ethanol and vacuum filtered and then dried in a heating oven (Binder GmbH, Germany) at 37 °C for 24 h. The total amylose content was determined using a modification of the ISO 6647 method [19]. The analytical curve was obtained using potato amylose (A - 0512, Sigma-Aldrich) and amylopectin (A - 8515, Sigma-Aldrich) standards. The inclusion of an amylopectin standard in the analytical curve followed the ISO 6647 guideline, helping to reduce the influence of background absorbance and improve the accuracy of amylose determination through iodine complexation. 100 mg of starch was weighed and 1 mL of ethanol (95% v/v) and 9 mL of a NaOH solution (1 mol/L) were added to a flask. The solution was kept in a boiling water bath for 10 min. After cooling, distilled water was added to complete 100 mL of solution in a volumetric flask. An aliquot of 0.5 mL was transferred into a test tube and 5 mL of distilled water, 0.1 mL of acetic acid (1 mol/L), 0.2 mL of iodine solution and additional distilled water were added to complete a reaction volume of 10 mL. This mixture was shaken vigorously and measured in the spectrophotometer at 620 nm. The percentage of amylose was calculated using equation 1.

$$\%Amylose = \frac{Abs \times K \times 100}{W} \quad (1)$$

Where, Abs is the sample absorbance, K is the analytical curve constant (obtained from curve data), and W is the sample weight (mg).

X-ray diffraction and relative crystallinity

Quinoa starch samples were kept for 10 days in a desiccator with a barium chloride solution (25 °C, water activity = 0.9) to standardize moisture before analysis. No defatting step was

performed prior to analysis. Afterwards, the samples were analyzed in the X-ray diffractometer (Miniflex II, Rigaku Corp., Tokyo, Japan) with Cu radiation to obtain the diffraction profiles. The working parameters were scanning speed of 2°/min and angle 2θ, varying from 4° to 50°, the current was 15 mA and voltage 30 kV. The relative crystalline creation was obtained by separating the crystalline peaks from the amorphous region using the method described by Frost et al. [20] and the implementation for starches [21] using the Savitzky-Golay smoothing method. Each cultivar was analyzed using a single diffractogram, consistent with prior work on quinoa starch crystallinity [22, 23].

WAI, WSI, and SP

A modification of the procedure developed by Anderson et al. [24] was followed to determine the WAI, WSI, and SP. In a previously tared centrifuge tube, 1.25 g of starch (db) were weighed and 30 mL of distilled water, preheated to 60 °C, were added. The system was placed in a water bath at 60 °C for 30 min, stirring the suspension 10 min after starting the heating. The solution was centrifuged at 7000 rpm at room temperature (24 °C) for 20 min. Then, the supernatant was extracted, and the volume (mL) was measured. An aliquot of 10 mL was taken from the supernatant and placed on a previously tared plate before drying at 70 °C overnight. Subsequently, the weight of the plate with the soluble fraction and the centrifuge tube containing the gel was recorded. The indexes were determined according to equations 2, 3, and 4.

$$WAI = \frac{Gelweight(g)}{Sampleweight(g)} \quad (2)$$

$$WSI = \frac{Solubleweight(g) \times V(mL)}{Sampleweight(g) \times 10mL} \times 100\% \quad (3)$$

$$SP = \frac{Solubleweight(g)}{Sampleweight(g) \times (1 - \frac{WSI}{100})} \quad (4)$$

Pasting properties

The pasting properties (PT, PV, TV, peak time (PKT), peak temperature (PKTE), FV, breakdown viscosity(BV) (PV-TV), and SV (FV-TV)) of the starches were determined using a Rapid Visco Analyser (RVA Super 4, Newport Scientific, Australia) and the software "Thermocline" for Windows (version 3.0, Newport Scientific, Warriewood, Australia). This method follows the protocol used by Lindeboom et al. [25], based on AACC method 61 - 02, for evaluating starch pasting behavior using RVA. Three g of sample were weighed, and the moisture content was corrected to 14% with distilled water. This suspension was equilibrated at 50 °C for 60 s before being linearly heated for 7 min and 30 s to 95 °C and held at that temperature for 5 min, cooled for 7 min and 30 s to 50 °C and held at that temperature until completing the 23 min program. The stirring speed was 160 RPM throughout the experiment, which was performed 4 times for WAQ, WSQ, WKQ, BNQ, and 3 times for WIQ and RPQ.

Statistical analysis

The results were expressed as means values, followed by the standard deviation. Analyses of variance were performed using Tukey's HSD test in the statistical environment R (version 4.5.0) [26], the IDE RStudio (version 2025.05.0.496) [27] and the statistical procedures package "agricolae" [28].

Results and Discussion

Color of the purified starch

The moisture and color parameters of the purified starch samples are shown in table 1. The moisture content of the purified starches ranged from 9.39% - 11.30%. These values are consistent with those reported by Li et al. [15], who found moisture contents ranging from 8.7% to 14.0% in starches isolated from 26 quinoa samples. All values fall within the acceptable range for dried starch and are appropriate for further functional characterization. High L* values indicate high starch reflectance, so that varieties with white episperm showed the highest values (≥ 98.01), while cultivars with dark episperm (BNQ and RPQ) had the lowest values (≤ 97.74). On the a* axis, the starch samples of BNQ and RPQ also differed in having the highest values (slightly reddish, but less than 0.4) while the other samples had the lowest values (slightly greenish). On the b* axis all samples showed positive values (slightly yellow, but less than 1.6) although the BNQ and RPQ samples showed significantly higher values. Diaz-Valencia et al. [8] reported that whole grains of RPQ and BNQ had lower L* and a* values than WSQ and a Brazilian white cultivar (BRS "Syetetuba"), while RPQ and WSQ had the highest b* values. The highest values of b* relative to a* had already been reported by Shi et al. [17] for seed flours of Peruvian white cultivars (WKQ and "Blanca de Juli") and a darker Canadian cultivar (NQ94PT). Slightly negative values of a*, as shown by WSQ and WIQ starch, were also reported for the flour obtained from quinoa seeds mechanically peeled (bran layer removed) in the study of the Qingli no. 6 cultivar by Wang et al. [29], whereas Yang et al. [30] reported negative b* values for native starch of quinoa. The presence of cultivar-specific-col-

Table 1: Moisture, amylose content and colour parameters of quinoa starch.

Cultivar	Moisture (%)	Amylose (%)	Colour parameters		
			L*	a*	b*
WAQ	9.39 ± 0.35^{b}	26.03 ± 3.78^{a}	98.26 ± 0.17^{ab}	0.03 ± 0.00^{c}	1.02 ± 0.03^{d}
WSQ	9.90 ± 0.73^{ab}	27.36 ± 3.69^{a}	98.38 ± 0.21^{ab}	-0.07 ± 0.02^{d}	1.14 ± 0.03^{c}
WKQ	10.28 ± 0.48^{ab}	26.71 ± 2.29^{a}	98.01 ± 0.62^{abc}	0.00 ± 0.01^{c}	0.91 ± 0.00^{e}
WIQ	11.30 ± 0.50^{a}	26.98 ± 2.91^{a}	98.73 ± 0.16^{a}	-0.10 ± 0.01^{d}	0.99 ± 0.01^{d}
BNQ	10.28 ± 0.55^{ab}	27.98 ± 3.92^{a}	97.74 ± 0.35^{bc}	0.21 ± 0.02^{b}	1.23 ± 0.04^{b}
RPQ	11.21 ± 0.63^{a}	17.65 ± 2.84^{a}	97.32 ± 0.06^{c}	0.35 ± 0.01^{a}	1.55 ± 0.02^{a}

Note: Values followed by the same letter in the column do not differ (Tukey test, $p < 0.05$).

ored compounds that remain associated with the starch after extraction may explain why, even after undergoing the same process, starches from pigmented cultivars retained distinct color parameters compared to those from lighter seeds [8].

Amylose content

The amylose content of the starches of the six quinoa cultivars is presented in table 1. No significant difference was observed between the cultivars ($p > 0.05$), with the overall average content being 25.45 ± 4.43%. Compared to studies that also used an iodine-binding assay, the value of the present study was higher than that reported by Shi et al. [17] who determined the amylose content of a flour blend of WKQ and "Blanca de Juli" to be 12.9%. This discrepancy may be due to methodological differences, as amylose determination from whole flour can underestimate the actual content due to matrix interference, whereas the present study used isolated starch for improved accuracy. Atwell et al. [14] also reported low amylose content (11%) while Lorenz [31], Jimenez et al. [32] and Wang et al. [29] reported even lower values for US (9.28%), Argentine (7.45 - 9.45%) and Chinese (10.58%) varieties, respectively. Values closer to those of the present study were reported by Tari et al. [33] for an Indian cultivar (22.5%) and Inouchi et al. [34] for samples from Bolivia and Peru (24.7 - 27%). In their analysis of 26 commercial samples of quinoa from different origins, Li et al. [15] reported apparent amylose contents, also by an iodine-binding assay, between 23.3 - 25.7% for the samples originating from Peru. The average amylose content obtained for the six quinoa cultivars was higher than the values reported for amaranth (0.2%), wheat (21.70%) and potato (23.01%) starches by Lorenz [31]. A higher amylose content (33.68%) was reported by Yang et al. [30], who performed the reading at 590 nm. Wright et al. [35] have suggested that the differences with previous studies could be partially explained, besides the origin, cultivar and growing conditions, by the extraction and quantification method, besides the fact that a fraction of amylopectin also forms complexes with iodine [36]. Our values correspond to apparent amylose content as determined by the iodine-binding method; while some interference from amylopectin is possible, the use of an amylopectin standard in the calibration curve reduced this effect.

Reported amylose contents in quinoa starch vary substantially depending on the analytical method used. The iodine-binding assay (blue value method), which is still widely applied [9, 12, 30, 31, 33, 34, 37-40], provides what is referred to as apparent amylose content. This value can be influenced by lipids, proteins, and partial interaction of iodine with amylopectin chains, which may lead to overestimation [15, 41]. In contrast, actual amylose content is typically determined by chromatographic methods such as HP-SEC or GPC after enzymatic debranching, which separates starch components by molecular size [25, 37]. For instance, Lindeboom et al. [25] reported 5.83% apparent amylose using the blue value method, and 10.98% actual amylose using HP-SEC. Martinez [38] and Tang et al. [39] reduced precision of the blue value method at amylose levels below 15%. Despite these limitations, the iodine-binding method remains widely used due to its practicality, and recent studies continue to report consistent values using this approach [9, 22, 35, 40]. Jiang et al. [9] reported 9.43 - 10.90% using this method for four Chinese cultivars; Jan et al. [22] and Ando et al. [40] reported similar values for Indian and Bolivian samples, respectively. Enzymatic methods tend to yield lower values, such as 6.06 - 8.44% [41], 8.22 - 9.45% [13, 42-44], 15.67% [45], and 19.70% [41], depending on cultivar and analytical conditions. Li et al. [15] found that iodine-based values were 1.26 - 3.35 times higher than enzymatic results on the same samples. Qian and Kuhn [23] and Nascimento et al. [45] also showed that quinoa starch had higher amylose content than amaranth starch (1.2 - 7.8%), although some studies found the opposite [45]. These differences underscore the influence of both analytical method and cultivar origin [30-32] on the reported amylose content of quinoa starch.

X-ray diffraction and relative crystallinity

All quinoa cultivars showed a type-A diffraction pattern typical of cereal starch such as wheat [14], maize [12, 34], rice [34], and pseudocereals such as *C. pallidicaule* [43]. Four peaks were identified in the diffractograms of the quinoa samples corresponding to the angles (2θ): 15.18 ± 0.13, 17.14 ± 0.10, 17.98 ± 0.12 and 23.02 ± 0.14 (Figure 1). Similar peaks were reported for 5 different Chinese quinoa cultivars [9, 30], two Indian cultivars [22] and Canadian quinoa samples [44, 46]. All previous studies that analyzed X-ray diffraction of quinoa starch also found the same type-A pattern.

The relative crystallinity measured by the Frost method for the starches of WAQ, WSQ, WKQ, WIQ, BNQ, and RPQ were 13.80, 14.35, 14.52, 13.88, 13.52, and 13.70% respectively. The average relative crystallinity for all cultivars was 13.96 ± 0.39%. Using other peak fitting methods, different values of relative crystallinity of quinoa starch have been previously reported. These lower values may also reflect the analytical method used: the Frost method [20], implemented with Savitzky-Golay smoothing [21], tends to yield more conservative estimates by reducing overlap between crystalline and amorphous regions. Li and Zhu [47] also emphasized that crystallinity values can differ substantially depending on experimental parameters, variety, and the definition of amorphous background, and should therefore be interpreted with respect to the method used. Qian and Kuhn [23] reported a value of 35.4% for commercial samples, similar to the results for 3 Bolivian cultivars (36.3 - 39.6% [43]).

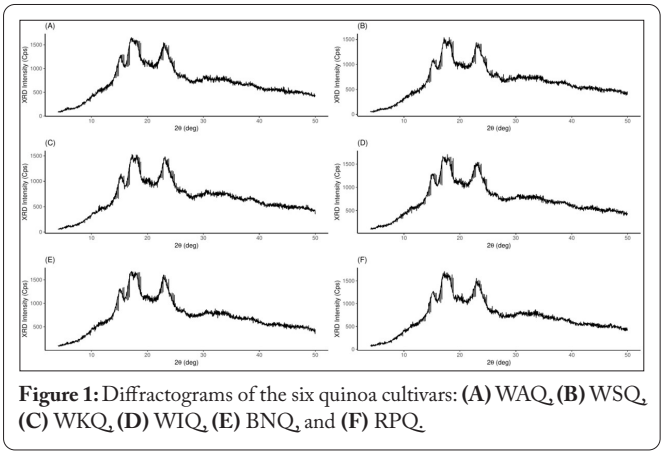

Figure 1: Diffractograms of the six quinoa cultivars: **(A)** WAQ, **(B)** WSQ, **(C)** WKQ, **(D)** WIQ, **(E)** BNQ, and **(F)** RPQ.

On the other hand, Jiang et al. [9] reported the lowest values of crystallinity (21.00 - 29.67%). In the same study, normal corn starch presented a higher relative crystallinity (36.05%) and higher amylose content (22.58%, by the blue value calculation) compared to quinoa starch samples, although for quinoa a variation in amylose content of 1.47% represented a variation in relative crystallinity of 8.67%, correlating negatively. The crystallinity of amaranth (45.5%) reported by Qian and Kuhn [23] was significantly higher than that of the quinoa they analyzed, although the amylose content (measured by the enzymatic method) of the quinoa was higher than that of amaranth. Steffolani et al. [43] found that the relative crystallinity (34.0 - 36.8%) of *C. pallidicaule* starch was slightly lower than that of their quinoa starch samples, while the amylose content (measured by the enzymatic method) of *C. pallidicaule* starch was significantly higher than that of quinoa.

Using the ratio of crystalline area to total area method (e.g. Hermann's method), Watanabe et al. [37] estimated the relative crystallinity of WKQ as 42.8%, while four other quinoa lines presented values between 39.0 (cultivar "Real") to 43%. Using the same method, Tang et al. [39] determined a lower relative crystallinity (35%) for the "Real" cultivar, although higher than barley (19.7%) and adzuki (25.5%) starches, while Tang et al. [39] reported lower relative crystallinity values for quinoa starches from Bolivian sweet (38%) and bitter (36.7%) cultivars than for garden orach starch (47.7%).

Jan et al. [22] reported crystallinity values between 21.46 and 22.19% for two Indian quinoa cultivars, which remain higher than those obtained in this study. Tang et al. [39] observed a negative correlation between crystalline and actual amylose content in quinoa and barley starches, while Tang et al. [39] reported that quinoa starch had significantly lower crystallinity than garden orach despite similar amylose levels. The effect of genotype interaction by sowing data on the composition of quinoa seeds has been reported by [3], but the effect of growing conditions on amylose content and crystalline of quinoa starch has not yet been comprehensively elucidated.

WAI, WSI, and SP

The values of WAI, WSI, and SP are shown in table 2. The WAI values showed no significant difference between the quinoa cultivars and had an average value of 8.36 ± 0.57 g/g, higher than previously reported for flour (3.08 g/g) and isolated starch (2.35 g/g) from the quinoa cultivar "Real" determined at 30 °C [12] and for native maize starch (7.5 g/g) determined at 95 °C [48]. Ahmed and Joseph [46] reported that higher temperature and smaller particle size significantly increased the water holding capacity of quinoa flour, similarly Ahmed et al. [44] reported an increase in the same parameter with increasing temperature for quinoa starch.

Table 2: WAI, WSI, and SP of the starches.

Cultivar	WAI (g/g)	WSI (%)	SP (g/g)
WAQ	8.29 ± 0.39^{a}	15.63 ± 0.35^{a}	18.53 ± 0.49^{a}
WSQ	8.30 ± 0.75^{a}	15.10 ± 0.94^{a}	17.79 ± 1.30^{a}
WKQ	8.70 ± 0.12^{a}	15.50 ± 0.05^{a}	18.34 ± 0.07^{a}
WIQ	8.08 ± 0.62^{a}	15.34 ± 0.88^{a}	18.13 ± 1.22^{a}
BNQ	8.81 ± 0.03^{a}	15.99 ± 0.35^{a}	19.04 ± 0.49^{a}
RPQ	8.11 ± 0.94^{a}	16.57 ± 1.16^{a}	19.87 ± 1.69^{a}
Mean	8.36 ± 0.57	15.70 ± 0.81	18.63 ± 1.15

Note: Values followed by the same letter in the column do not differ (Tukey test, $p < 0.05$). All analyses were performed three times, except for WKQ starch which was analysed in duplicate due to sample availability.

There was also no significant difference between the WSI of starches from different quinoa cultivars, averaging 15.70 ± 0.81%. Ahmed et al. [49] reported a higher value (43.78%) determined at 70 °C for a quinoa flour with 86.23% starch, compared to the value they got at 25 °C. Another quinoa flour also had a significantly higher WSI determined at 70 °C (21.94%) than at 25 °C [46]. Even when WSI was measured at 30 °C, quinoa flour showed higher solubility (10.62%) than isolated quinoa starch (4.56%) [12], which was attributed to residual non-starch compounds in flour (e.g., fiber) that promote solubilization. These findings are in agreement with the values obtained in the present study, which were considerably higher than those reported by Lorenz [31] (1.14% determined at 60 °C for starch with an amylose content of 9.28%), Jan et al. [22] (1.32 - 2.72% determined at 55 °C; 1.47 - 2.80% determined at 65 °C), and Ahamed et al. [50] (~4 - 6.5%, determined between 65 and 95 °C). This may be due to varietal differences, methodological factors, and the fact that 60 °C is close to the pasting onset temperature (58.68 - 62.06 °C) of the samples analyzed, as indicated by RVA measurements, which facilitates early gelatinization and greater solubilization (Table 3).

Although some authors have proposed that higher amylose content restricts solubility [36], the relatively high amylose content of our samples (25.45 ± 4.43%) did not appear to suppress WSI. In contrast, Lorenz [31] observed that low-amylose starches exhibited low solubility, with water binding increasing only upon heating. Ahamed et al. [50] likewise attributed the higher solubility of maize starch to its greater amylose content, although this was based on assumed values

Table 3: Pasting properties of quinoa starch.

Cultivar	PT (°C)	PKT (min)	PKTE (°C)	Viscosity (cP)				
				Peak	Trough	Breakdown	Final	Setback
WAQ	60.21 ± 0.69^{ab}	10.13 ± 0.64^{a}	94.74 ± 0.18^{a}	3408 ± 171^{a}	2979 ± 215^{a}	430 ± 174^{bc}	4452 ± 256^{a}	1474 ± 278^{ab}
WSQ	60.40 ± 0.33^{ab}	10.25 ± 0.23^{a}	95.11 ± 0.06^{a}	3136 ± 166^{a}	2805 ± 320^{a}	332 ± 209^{c}	4320 ± 178^{a}	1516 ± 223^{ab}
WKQ	59.88 ± 0.85^{ab}	10.10 ± 0.16^{a}	94.48 ± 0.46^{a}	3414 ± 115^{a}	2709 ± 111^{ab}	704 ± 35^{ab}	4531 ± 89^{a}	1822 ± 55^{a}
WIQ	58.68 ± 2.58^{b}	9.80 ± 0.13^{a}	95.08 ± 0.24^{a}	3020 ± 68^{a}	2555 ± 116^{abc}	465 ± 151^{bc}	4130 ± 92^{ab}	1574 ± 94^{ab}
BNQ	62.06 ± 1.06^{a}	10.15 ± 0.33^{a}	95.05 ± 0.31^{a}	2241 ± 346^{b}	2076 ± 298^{c}	164 ± 82^{c}	2908 ± 482^{c}	831 ± 224^{c}
RPQ	59.40 ± 1.31^{ab}	8.82 ± 0.08^{b}	94.90 ± 0.93^{a}	3159 ± 49^{a}	2195 ± 102^{bc}	964 ± 53^{a}	3543 ± 97^{b}	1348 ± 6^{b}

Note: Values followed by the same letter in the column do not differ (Tukey test, $p < 0.05$). Each analysis was performed three times.

rather than direct measurements. These differing conclusions suggest that the relationship between amylose content and WSI is not universal and may be influenced by analytical conditions, starch structure, and the temperature at which solubility is assessed. Thus, although Li and Zhu [36] reported a negative correlation between amylose and WSI in quinoa starches based on other literature, our findings indicate that high WSI values may still occur in samples with relatively high amylose content when measured near their gelatinization onset.

The SP of the starch of the six quinoa cultivars did not show significant differences between them. The average SP values obtained in the present study were higher than those reported by Lorenz [31] (10.61 g/g) at the same temperature (60 ˚C), and fell within the ranges reported by Li et al. [15] for SP determined at 65 ˚C (12.54 - 20.31 g/g) for quinoa seed starches of different origin; and also within the range reported by Lindeboom et al. [25] determined at 65 ˚C (10.3 - 20.7 g/g) also for quinoa starches. Li et al. [15] indicated that the SP of most quinoa starches showed a constant increase from 55 to 85 ˚C. This temperature behavior was also observed by Jan et al. [22], who reported an increase in the SP of two quinoa cultivars from 55 ˚C (1.72 - 2.1 g/g) to 95 ˚C (12.53 - 13.89 g/g). At 90 ˚C, Yang et al. [30] reported a similar value as percentage (13.34%). Between 60 and 90 ˚C, quinoa starch had a higher SP than wheat, barley, wild rice and amaranth starch [31].

However, comparative results for quinoa and other starch sources, e.g. corn starch, vary. Ahamed et al. [50] reported that quinoa starch had a lower SP than corn starch at both 65 and 95 ˚C (about 6.5 and 8.5 g/g, respectively), whereas Jiang et al. [9] observed that SP values for four quinoa cultivars were higher than that of corn starch from 65 - 85 ˚C. This apparent contradiction may be explained by differences in starch source and methodology. For instance, Ahamed et al. [50] did not report actual amylose contents but assumed values from literature (corn: 23 - 24%; quinoa: ~11%), whereas Jiang et al. [9] measured them directly, reporting 9.43 - 10.90% for quinoa and 22.58% for corn. These last authors attributed the higher SP of quinoa to its smaller granule size and lower amylose content, which would allow easier hydration. Lindeboom et al. [25] also found a negative correlation between amylose content and SP, which supports that low-amylose starches may swell more readily. However, in our study, although amylose content was relatively high, SP values were still considerable, suggesting that other structural factors (e.g., damaged starch or granule architecture) may play a role. Additionally, as noted by Li and Zhu [36] and Ahmed et al. [44], differences in experimental conditions, such as starch concentration, separation methods, and presence of damaged starch, can significantly affect SP measurements.

Pasting properties

The pasting properties of the starch of the six quinoa cultivars are shown in table 3. Overall, the pasting profiles of the quinoa starches analyzed followed the typical pattern of starches obtained from other cereals and roots [23, 35]. It can also be seen that BNQ and RPQ had slightly different viscosity behavior than the starch of the other cultivars (Figure 2). BNQ starch had the highest PT (62.06 ˚C) while WIQ had the lowest (58.68 ˚C). These values are within the range reported (51.3 – 65.8 ˚C) by Li et al. [15] for quinoa starches of different origin. PT values (62.7 - 93.65 ˚C) higher than those in the present study were also previously reported [9, 22, 23, 30, 35, 43]. Higher PT values were reported for other pseudocereals such as amaranth (71.7 ˚C) [23], *C. pallidicaule* (71.1 - 74.7 ˚C) [43], roots such as potato (67.90 ˚C) [9] and cereals such as corn (75.5 - 75.93 ˚C) [9, 35]. PT is related to the minimum temperature for cooking starch [22, 43] and losing birefringence of the starch granule [14]. A low PT, as obtained for WIQ starches, has been associated with higher hot paste stability and resistance to shear thinning during cooking [23], although BV is more commonly used as the primary indicator of thermal and mechanical stability. On the other hand, high PT values of quinoa starches from other cultivars showed that they are more difficult to swell and break [9]. Steffolani et al. [43] got a positive correlation between amylose content (determined by the enzymatic method) and PT for quinoa and kañiwa starches. However, Jan et al. [22] found that the starch of the quinoa cultivar with the lowest amylose content (determined using the blue value) obtained the highest PT, suggesting that PT could be affected by other factors. In the case of quinoa flour, the smaller particle size significantly lowered the gelatinization temperature (from 72.9 - 60.8 ˚C) [49], so the effect of quinoa starch particle size on pasting properties such as PT should be reviewed.

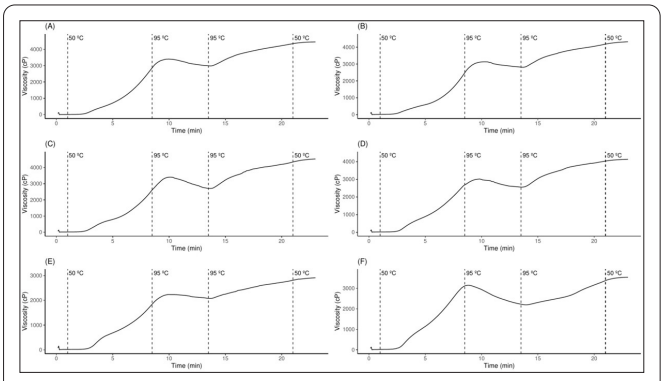

Figure 2: Pasting profiles of quinoa starches: **(A)** WAQ, **(B)** WSQ, **(C)** WKQ, **(D)** WIQ, **(E)** BNQ, and **(F)** RPQ.

The PV of starch from all cultivars did not differ significantly, except for BNQ which had the lowest PV. Starch from the other cultivars was in the range reported in [9, 30] (2640 - 3551 cP). Much higher PV values have also been reported in the literature for samples of quinoa starch from different origins (3756 - 5376 cP, 1 RVU = 12 cP) [15, 22, 23, 35, 51].

The PV of BNQ is higher than that reported by Jan et al. [22] for an Indian cultivar (2488 cP, 1 RVU = 12 cP), while another cultivar from the same germplasm bank showed a higher PV (4636.8 cP, 1 RVU = 12 cP) than all the starches analyzed in the present study. Our PV values for the starches of the six quinoa cultivars were higher than those reported by Qian and Kuhn [23] for amaranth starch (1662 cP, 1 RVU = 12 cP) and by Srichuwong et al. [13] for wheat starch (1319 cP), but lower than that reported by Wright et al. [35] for corn starch (4830 cP, 1 RVU = 12 cP) and by Jiang et al. [9] for potato starch (4144 cP). The PV values obtained for starch from all cultivars

were also higher than those reported by Goh and Lee [52] for flour from Peruvian white quinoa (1694.04 cP, 1 RVU = 12 cP) and by Ballester-Sánchez et al. [11] for black and red quinoa flours (942 and 1084 cP, respectively), although lower than those reported by Contreras-Jiménez et al. [12] for "Real" quinoa flour (3154.2 cP, 1 cP = 1 mPa s). In the latter study it was suggested that because it contained a higher amount of fat, quinoa flour had a lower PV than its starch. The method of obtaining the quinoa flour also varies from PV [25]. A high PV value indicates higher water-binding capacity, a higher degree of swelling of the starch granules and higher thickening power of the starch during high-temperature heating [15, 22, 43]. Lindeboom et al. [25] and Steffolani et al. [43] have reported that the amylose content (determined by HP-SEC and enzymatic assay) of quinoa starch was negatively related to PV, while Li et al. [15] pointed out that the correlation between PV and apparent amylose content (measured by a colorimetric iodine assay) was positive. Srichuwong et al. [13] reported a parabolic correlation between PV and amylose content (determined by an enzymatic assay) of whole quinoa flour. We were unable to observe a positive or negative correlation of amylose content (determined by a colorimetric iodine assay) on the PVs of the quinoa starches analyzed in this study. Li and Zhu [36] previously showed that the relationship between amylose content and PV of quinoa starch is complicated and that other factors such as granule size and super long chains in amylopectin may also affect PV.

The PKT for all cultivars, except RPQ, did not differ significantly, being between 9.80 to 10.25 min. The PKT of RPQ was significantly lower (8.82 min). Using a pasting program of the same length (23 min), Shi et al. [17] reported a PKT value of 12.9 min for a flour mixture of the Peruvian cultivars WKQ and "Blanca de Juli", while another flour from a Canadian cultivar showed a PKT of 9.1 min. Ahmed et al. [49] reported a PKT for another quinoa flour of 10.9 min, using a longer pasting program (28 min). In the quinoa flour, the PKT may vary slightly with the method of preparation of the flour [29]. The PKTE of the six cultivars analyzed was not significantly different and averaged 94.88 ± 0.44 °C. This value was slightly higher than the range reported by Li et al. [15] (75.5 - 94.1 °C) for 26 samples of isolated quinoa starch but lower than the PKTE reported in Ahmed et al. [49] for whole quinoa flour (94.8 °C).

Starches from white cultivars (WAQ, WSQ, WKQ and WIQ) showed the highest TV values (2555 - 2979 cP), while RPQ and BNQ starches showed the lowest values. The TVs of all cultivars were in the range reported [15, 23, 35] for quinoa starches from different origins (897.6 - 4432.8 cP, 1 RVU = 12 cP). All the starches of cultivars analyzed in the present study presented higher TV values than those reported by Jiang et al. [9] for potato starch (1492 cP) and corn starch (1794 cP). On the other hand, Wright et al. [35] reported a higher TV value for corn starch (2368.8 cP, 1 RVU = 12 cP) than BNQ and RPQ. Li et al. [15] reported a positive correlation between the TV of quinoa starch and the apparent amylose content determined by a colorimetric iodine assay, however in this study RPQ presented the lowest TV although it had a similar amylose content to the other cultivars. The lower PV and TV value of BNQ starch compared to the other cultivars resulted in the lowest BV. Steffolani et al. [43] reported that high PV values were associated with high BV values. In the case of RPQ, its high PV caused it to have an even higher BV than starches from white cultivars, which had values between 332 - 704 cP. These values were within the range of BV (113 - 2616 cP, 1 RVU = 12 cup) previously reported in [15, 35, 51] for quinoa starches of different origin. Our BV values were lower than those reported by Qian and Kuhn [23] for amaranth starch (870 cP, 1 RVU = 12 cP), by Wright et al. [35] for corn starch (1710 cP, 1 RVU = 12 cP) and by Jiang et al. [9] for potato starch (2653 cP). Low BV values, such as BNQ and WSQ, show greater stability against shear thinning and high-temperature heating [15, 23, 35]. The relatively high PV of WAQ and WSQ starches, together with their low BV, would make them desirable for some industrial and food applications [22].

The FVs of starches from white cultivars were the highest in the range 4130 - 4452 cP, followed by RPQ and BNQ which had the lowest value. The FV of starches from light-colored cultivars and RPQ were between the values reported in [9, 15, 23, 30, 35, 51] (2932 - 5951 cP, 1 RVU = 12 cP) for quinoa starches from different sources. The VF of BNQ starch was only higher than that reported for starch from an Indian quinoa cultivar (2684 cP) analyzed by Jan et al. [22] and slightly lower than the VF of corn starch (2966 cP) reported by Jiang et al. [9]. The FV of starch from all cultivars analyzed in this study was higher than that reported for amaranth starch (1296 cP, 1 RVU = 12 cP) by Qian and Kuhn [23] and that reported by Jiang et al. [9] for potato starch (1660 cP). Li et al. [15] reported a positive correlation between the FV of quinoa starch and the apparent amylose content (determined by a colorimetric iodine assay), while Lindeboom et al. [25] (for quinoa starches) and Steffolani et al. [43] (for quinoa and kañiwa starches) observed a negative relationship between FV and amylose content (determined by HP-SEC and enzyme assay). In the present study no positive or negative relationship was observed between FV and amylose content (determined by a colorimetric iodine test) of starch from the six analyzed cultivars.

The SV values of the analyzed starches followed a similar trend to their PV values, with BNQ getting the lowest value. The SV of starches from white cultivars and RPQ ranged from 1348 to 1822 cP, being in the range reported in [15, 23, 35] for quinoa starches of different origin (1164 - 2136 cP, 1 RVU = 12 cP). A lower SV range (442 - 963 cP) was reported for Bolivian, Indian, and Chinese cultivars [9, 22, 43], with values closer to the SV of BNQ, while Wilhelm et al. [51] reported an even lower SV for starch from a Bolivian quinoa (132 cP, 1 RVU = 12 cP). The SV of all six cultivars analysed was higher than that reported by Jiang et al. [9] for potato starch (395 cP) and by Qian and Kuhn [23] for amaranth starch (504 cP, 1 RVU = 12 cP). Only the SV of BNQ showed lower values than those reported by Steffolani et al. [43] and Jiang et al. [9] for *C. pallidicaule* (1041 - 1332 cP) and maize (1172 cP) starch, respectively. The SV reflects the extent of starch retrogradation, which is associated with the re-association of amylose and amylopectin molecules during cooling. This parameter has been linked to the firmness and rigidity of starch gels, characteristics relevant in applications where texture retention after cooling is critical, such as in baked or chilled foods [15, 43].

Steffolani et al. [43] and Jiang et al. [9] observed that a higher amylose content (determined by enzymatic testing and calculation of the blue value) corresponded to higher SV values. However, the low SV value of BNQ starch did not correspond to a lower amylose content (determined by iodine colorimetry) in the present study. The relatively low SV of BNQ and RPQ starch, as well as their PV values (especially for RPQ), would make them attractive for use in foods that must maintain their consistency after cooling, such as instant creamy desserts [43].

Conclusion

The functional and pasting properties of six Peruvian quinoa cultivars of different colors were evaluated. Slight differences in starch color suggest the presence of residual pigmented compounds. The amylose content, determined by a colorimetric iodine assay, did not significantly differ among cultivars, and was within the upper range of previously reported values using similar methods. However, complementary analysis using enzymatic assays and assessments of damaged starch, fiber, protein, and mineral content are recommended to better explain variations in starch functionality. No significant differences were observed among cultivars for the functional properties measured, which were generally higher than previously reported values. Pasting properties, particularly the lower PV of BNQ and shorter PKT of RPQ, indicate cultivar-specific behaviors that may inform their selection for tailored food applications.

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Conflict of Interest

None.

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