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RECEIVED 15 December 2025

REVISED 10 March 2026

ACCEPTED 11 March 2026

PUBLISHED 26 March 2026

CITATION

Rossi F, Giuberti G, Dall'Asta M, Cervini M,
Dodi R, Melo Ortiz DI, Fiorini A and
Tabaglio V (2026) Nutritional
characterization of three quinoa
(*Chenopodium quinoa* Willd.) cultivars
grown in northern Italy.
Front. Food Sci. Technol. 6:1768332.
doi: 10.3389/frfst.2026.1768332

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Nutritional characterization of three quinoa (*Chenopodium quinoa* Willd.) cultivars grown in northern Italy

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Introduction: Gluten-free foods are often characterized by reduced dietary fibre content, a high glycemic index, low iron and calcium concentrations, and limited protein quality. Quinoa (*Chenopodium quinoa* Willd.) is a gluten-free pseudocereal whose nutritional composition varies depending on the cultivar and on pedoclimatic conditions. The introduction of quinoa into European agroecosystems, particularly in Italy, diversifies crop rotations, thereby improving agrobiodiversity. Within this framework, this study investigated the potential cultivation of quinoa under the pedoclimatic conditions of the Po Valley (northern Italy) and evaluated how these conditions influence the qualitative traits of cultivars adapted to environments markedly different from their areas of origin.

Methods: We analyzed three of the most widely cultivated quinoa cultivars (Regalona, Titicaca, and Vikinga) grown in northern Italy.

Results: Titicaca showed the highest total dietary fiber (13.7%) and iron content (8.31 ± 0.67 mg 100 g⁻¹). The protein score ranged from 75 (Leu) in Vikinga to 77 (Leu) in Titicaca. Resistant starch accounted for 6.1% (Titicaca) to 7.5% (Vikinga) of total starch. Overall, quinoa represents a promising gluten-free food and a potentially valuable crop for diversifying European agroecosystems.

Discussion: Compared to corn and rice, quinoa has a higher Ca and Fe content, therefore its inclusion in gluten-free products would improve its nutritional value. The 3 quinoa cv showed a higher protein content than corn and rice. The lysine content was also higher than that of the two gluten-free grains. Overall, quinoa represents a promising gluten-free food and a potentially valuable crop for diversifying European agroecosystems.

KEYWORDS

gluten-free food, nutrients, protein score, pseudocereals, quinoa

1 Introduction

Coeliac disease (CD) is a chronic enteropathy caused by exposure to dietary gluten in genetically predisposed individuals, with a global prevalence of approximately 1% (Gujral, et al., 2012). The only effective treatment for CD is a lifelong adherence to a gluten-free (GF) diet. Compared to their gluten-containing counterparts, GF products generally have lower dietary fiber content, higher glycemic index, reduced protein levels, and elevated fat and salt

contents, as well as lower levels of key micronutrients (e.g., calcium, iron, folic acid) (Pellegrini and Agostoni, 2015; Morreale et al., 2018).

Quinoa (*Chenopodium quinoa* Willd.) is an annual pseudocereal belonging to the Amaranthaceae family. In recent years, GF crops such as quinoa have attracted growing interest due to their high nutritional value and adaptability to challenging environmental conditions (Rezzouk et al., 2020). Nutritional indication suggested that quinoa grains and derived flours are rich in minerals, phenolic compounds, dietary fiber, and polyunsaturated fatty acids, and are also an excellent source of high-quality protein (Martinez-Villaluenga et al., 2020; Alasalvar et al., 2021; Li et al., 2025).

Furthermore, quinoa has been classified as a low-glycaemic index (GI) and low-glycaemic load (GL) food (Ballester-Sánchez et al., 2019; Zhang et al., 2022). Accordingly, the inclusion of quinoa flour in bakery products has been reported to improve their overall nutritional profile by increasing the protein, micronutrient, and fiber contents, as well as by lowering the *in vitro* GI while increasing the slowly digestible starch (SDS) and resistant starch (RS) contents (Ballester-Sánchez et al., 2019; Xu et al., 2019). Increasing the SDS and RS content in cereal-based foods can offer several nutritional benefits, particularly in the areas of the glycemic control, colonic health, and chronic disease prevention (Chisbert et al., 2024).

The aim of this study was to evaluate the nutritional composition (macronutrients and minerals), starch digestibility, and protein scores (PS) of three quinoa cultivars grown in northern Italy – an area significantly different from the native quinoa growing regions – where this crop may provide a viable alternative to wheat and other cereals, especially in hilly areas.

2 Materials and methods

2.1 Samples

Three quinoa cultivars (Regalona, Titicaca, and Vikinga) were cultivated in Argenta, in the Po Valley (Northern Italy; 44.633 882 N, 11.834307 E), on a commercial farm. The main soil characteristics were as follows: clay texture (USDA classification); clay 563 g kg⁻¹, silt 393 g kg⁻¹, sand 44 g kg⁻¹; pH 7.6; organic matter 2.26%; total Kjeldahl nitrogen 0.121%; C:N ratio 10.8; Olsen P 8.2 mg kg⁻¹; exchangeable K 138 mg kg⁻¹; and cation exchange capacity 44.9 cmol kg⁻¹.

A split-plot field trial with four replicates was established in April 2024 and harvested in August. Quinoa grain from each replicate was subsampled and analyzed to determine its nutritional composition.

2.2 Nutritional composition

2.2.1 Macronutrients

Grains were dried at 55 °C in a forced air oven to constant weight. Dried grains were ground through a 1-mm screen (Retsch grinder model 26 ZM1; Brinkman Instruments, Rexdale, ON,

Canada) and analyzed for their dry matter (DM; AOAC method 930.15; AOAC, 2002), ash (AOAC method 942.05; AOAC, 2002), crude protein (AOAC method 976.05; AOAC, 2002), crude lipid (AOAC method 954.02 without acid hydrolysis; AOAC, 2002), total, insoluble and soluble dietary fiber (Megazyme assay kit K-INTDF), total starch (Megazyme assay kit K-TSTA), and total sugar (Megazyme assay kit K-SUFRG) contents.

2.2.2 Minerals

The concentration of the following mineral: Ca, P, Mg, Fe, Cu, Zn, was determined using atomic absorption spectroscopy following the EPA standards (U. S. EPA, 2014a; U. S. EPA, 2014b).

2.2.3 Amino acids

Amino acids were determined using an AA analyzer (Jasco, Inc., Easton, MD, United States) using the hydrolysis methods described by Moore (1963), Eggum (1968), and Moore et al. (1980). The PS was calculated using the formula proposed by (Millward, 2012):

$$PS = \frac{\text{Concentration of each EAA (g/100 g protein)}}{\text{Concentration of each EAA (g/100 g protein) in the WHO – FAO amino acids reference list}} \times 100$$

where:

EAA = essential amino acid

The lower value of this ratio represents the PS (Millward, 2012).

2.2.4 Starch digestibility

Quinoa grains were washed with distilled water three times, after which they were soaked in distilled water at a 1:2 ratio/grains:water by weight for 1 h at room temperature. Then, the grains and soaking water were transferred to a glass container and heated at 100 °C to assess the optimal cooking time (OCT). The OCT was reached once the white core of the cooked grains had disappeared, after compression between two glass slides (Chen et al., 2022). The OCT were 13'30" for Regalona, 11'00" for Titicaca and 15'00" for Vikinga. *In vitro* starch digestion of the cooked quinoa was carried out following the Englyst method (Englyst et al., 2018). The *in vitro* glucose release after 20 min of the intestinal phase, and between 20 min and 120 min, were measured colorimetrically (GODPOD 4058, Giese Diagnostic S.n.c., Rome, Italy) and calculated as both rapidly digestible starch (RDS) and SDS. Available starch (AvS) was calculated as the sum of RDS and SDS. Slowly digestible starch/available starch (SDS/AS) was calculated based on the SDS and AS contents. Samples were analyzed in triplicate. The RS was measured on OCT samples using an enzymatic assay kit (Megazyme Ltd., Bray, Ireland).

2.3 Statistical analysis

The data were analyzed using PROC ANOVA in SAS 9.4 (SAS Inst., Cary, NC, United States) and Tukey as post-hoc test. The normality check in the data distribution was performed using the SAS 9.4 statistical software (PROC UNIVARIATE).

TABLE 1 Macronutrients content (on dry matter basis) of quinoa *cultivars* compared with other gluten-free raw material from USDA FoodData Central (mean, minimum and maximum value).

Food	Protein (%)	Lipid (%)	Starch (%)	Ash (%)	Dietary fiber (%)	Insoluble fiber (%)	Soluble fiber (%)
Titicaca	18.6 ± 0.4	4.8 ± 0.1 ^a	54.8 ± 0.5 ^a	3.9 ± 0.15	13.7 ± 0.6 ^b	9.6 ± 0.2 ^b	4.0 ± 0.4
Regalona	18.6 ± 0.2	4.7 ± 0.1 ^a	59.4 ± 0.5 ^c	3.1 ± 0.09	10.2 ± 0.5 ^a	6.6 ± 0.7 ^a	3.6 ± 0.3
Vikinga	18.1 ± 0.4	5.6 ± 0.3 ^b	57.9 ± 0.7 ^b	3.3 ± 0.07	10.9 ± 0.8 ^a	7.0 ± 0.5 ^a	3.9 ± 0.3
Wheat whole flour. NDB n° 20080 ¹	15.1 (13–16.7)	2.7 (2.5–3.7)	71.2 (calculated)	1.6 (1.3–2.0)	10.6 (8.5–11.4)		
Maize, flour NDB n°100251	7.0 (6.1–7.6)	1.9 (1.1–3.2)	90.2 (calculated)	0.50 (0.3–0.8)	4.9 (4.3–5.1)	-	-
Rice, white, flour. NDB n° 20061	7.8 (7.1–8.6)	1.5 (1.2–1.7)	90.8 (calculated)	0.4 (0.3–0.6)	0.6 (0.2–0.7)	-	-

^{a,b,c} Data concerning the 3 *cultivars* of quinoa are expressed as mean ± standard deviation (SD). Data in the same column with different letters are different at $p < 0.05$.

¹Data from USDA (2021).

TABLE 2 Mineral content (mg/100 g on dry matter basis) of the three *cultivars* of quinoa analyzed in this research and in whole soft wheat (*Triticum aestivum*) or ingredients for gluten-free products from USDA FoodData Central (mean, minimum and maximum value).

Food	Fe	Cu	Zn	Ca	Mg	P
Titicaca	8.31 ± 0.67 ^b	0.63 ± 0.11	4.04 ± 0.46	170 ± 40 ^b	210 ± 20	290 ± 50
Regalona	5.16 ± 0.40 ^a	0.77 ± 0.10	3.46 ± 0.14	140 ± 10 ^{ab}	220 ± 20	310 ± 70
Vikinga	5.67 ± 0.37 ^a	0.76 ± 0.07	3.28 ± 0.48	120 ± 10 ^a	200 ± 10	300 ± 10
Wheat whole flour. NDB n° 20080 ¹	3.86 (2.9–4.5)	0.45 (0.37–0.65)	3.24 (2.21–5.34)	38 (33–48)	136 (117–151)	352 (252–470)
Maize, flour, NDB n°100251	4.44 (2.33–7.79)	0.082 (0.04–0.13)	0.62 (0.32–0.96)	0 (0–0)	30.1 (12.4–51.8)	92 (46–158)
Rice, flour, white NDB n°20061	0.22 (0. – 0.7)	0.21 (0.16–0.36)	1.19 (0.93–1.54)	6.0 (4–12)	22.9 (11.9–34.8)	94 (68–123)

^{a,b,c} Data concerning the 3 *cultivars* of quinoa are expressed as mean ± standard deviation (SD). Data in the same column with different letters are different at $p < 0.05$.

¹Data from USDA (2021).

All parameters were normally distributed except for lipids, ash, and Fe. For these parameters, analysis of variance was performed using the logarithmic transformation.

3 Results

3.1 Macronutrients and mineral content of the quinoa cultivars

3.1.1 Macronutrients

The macronutrient contents of the three quinoa cultivars are presented in Table 1. The nutrient composition of common wheat (*Triticum aestivum* subsp. *aestivum*), maize (*Zea mays* L.), and rice (*Oryza sativa* L.) were retrieved from the United States Department of Agriculture FoodData Central database (USDA, 2021) for comparing the data obtained from the analysed cultivars.

Titicaca showed significantly higher contents of total and insoluble dietary fiber compared to Regalona and Vikinga ($P < 0.05$). In contrast, Regalona had the highest starch content, followed by Vikinga and Titicaca ($P < 0.05$). Vikinga exhibited the highest

lipid content of the three cultivars. No significant differences were observed in protein, ash, or soluble fiber contents.

3.1.2 Minerals

The mineral contents of the three quinoa cultivars are reported in Table 2. Titicaca had a higher iron content than the other cultivars (8.31 vs. 5.16 and 5.67 mg/100 g for Regalona and Titicaca respectively; $P < 0.05$), with a 2-fold increase compared with maize (4.44 mg/100 g). The calcium content was also higher in Titicaca than in Regalona (170 vs. 120 mg/100 g; $P < 0.05$) but not than in Vikinga (140 mg/100 g). The calcium content of quinoa was more than 20-fold higher than rice, while maize contained only traces of this mineral. No significant differences in copper, zinc, magnesium, and phosphorus were found between the three quinoa varieties.

All three quinoa cultivars showed higher mineral contents compared with maize and rice.

3.1.3 Amino acid patterns of quinoa cultivars

Table 3 shows the amino acid composition of the three quinoa cultivars. The only significant difference was in relation to tyrosine content, which was higher in Regalona and Vikinga than in Titicaca

TABLE 3 Amino acid content (g/100 g protein) and Protein Score according to WHO-FAO of the three cultivars expressed by the percentage of amino acid requirements estimated by WHO-FAO (n = 4).

Item	Thr	Val	Ile	Leu	Tyr ¹	Phe ¹	His	Lys	Trp	Met	Protein score	
											6 months	Adults
Titicaca	3.51	4.69	4.03	6.04	2.45 ^a	3.90	3.46	4.57	0.69	1.77	74 Lys	77 Leu
Regalona	3.57	4.58	4.07	6.18	2.79 ^b	4.07	3.46	4.79	0.97	2.04	74 Lys	76 Leu
Vikinga	3.43	4.40	3.77	5.82	2.82 ^b	3.87	3.38	4.46	0.77	1.93	73 Lys	75 Leu
RMSE	0.1150	0.2590	0.1520	0.2235	0.1468	0.2084	0.1292	0.1858	0.2037	0.1909		
WHO-FAO ²	3.45	4.83	3.59	7.34	5.87 ¹		2.23	6.33	0.95	3.06		
WHO-FAO ³	1.52	2.57	1.98	3.89	2.51 ¹		0.99	2.97	0.40	2.51		

^{a,b} Data in the same column with different letters are different at p < 0.05.

¹For the calculation of Protein Score, these amino acids are considered together.

²At 6 months of age, assuming a growth requirement of 0.46 g of protein/kg of body weight/day and a maintenance requirement of 0.66 g of protein/kg of body weight/day.

³After 18 years of age, assuming no growth requirement and a maintenance requirement of 0.66 g of protein/kg of body weight/day.

Thr, Threonine; Val, Valine; Ile, Isoleucine; Leu, Leucine; Tyr, Tyrosine; Phe, Phenylalanine; His, Histidine; Lys, Lysine; Met, Methionine.

TABLE 4 Starch fractions (g/100 of product cooked as eaten) and optimal cooking time (minutes) of the 3 cv of quinoa.

CULTIVAR	OCT	SDS	RDS	RS	AvS	SDS/AvS	RDS/AvS
Titicaca	11' 00"	5.36 ^{ab}	7.77 ^A	3.33 ^A	13.13	40.78 ^B	59.22 ^A
Regalona	13' 30"	4.50 ^a	9.36 ^B	4.06 ^B	13.86	32.53 ^A	67.47 ^B
Vikinga	15' 00"	5.48 ^b	7.70 ^A	4.33 ^B	13.19	41.51 ^B	58.48 ^A
RMSE	-----	0.463472	0.535640	0.157251	0.839915	1.927291	1.927291

a,b (P < 0.05) A,B (P < 0.01).

OCT, Optimal Cooking Time SDS, slowly digestible starch; RDS, rapidly digestible starch; RS, resistant starch; AvS = available starch; SDS/AvS = percentage of SDS, on AvS; RDS/AvS.

(by about 14%–15%). The WHO-FAO PS is determined by the limiting amino acid, which is lysine for children 6 months of age and leucine for adults. When calculated for children, the resulting values were 74 for Titicaca and Regalona and 73 for Vikinga; for adults, the values were 77 for Titicaca, 76 for Regalona, and 75 for Vikinga.

3.1.4 Starch fractions

The *in vitro* digestion of starch as RDS, SDS and RS of cooked quinoa samples is presented in Table 4. When cooked to their optimum, the three quinoa grain varieties exhibited a similar total AvS content, being, on average, 13.4 g/100 g. Referring to the individual content of the starch fractions (i.e., RDS, SDS and RS), Regalona had the lowest SDS content (i.e., 4.50 g/100 g; P < 0.05) and the highest RDS content (i.e., 9.36 g/100 g) compared with the other varieties. The greatest level of RS was found in the Regalona and Vikinga varieties, being on average 4.2 g/100 g of cooked product. Accordingly, the SDS/Av ratio exceeded the 40% threshold in the varieties Titicaca and Vikinga.

4 Discussion

4.1 Macronutrients

The protein, lipid, and total dietary fiber contents measured in the three quinoa cultivars analyzed in this study fell within the range

reported by Martinez-Villaluenga et al. (2020). However, the protein content (18.1%–18.6% on a DM basis) was markedly higher than the average levels reported by Craine and Murphy (2020) and Zhang et al. (2022), which were 12.6% and 14.3%, respectively. The absence of significant differences in protein content between Regalona and Titicaca had already been observed by Reguera et al. (2018). Regarding the total dietary fiber, the predominance of the insoluble fraction was evidenced, which accounted for approximately two-thirds of the total fiber, in agreement with the findings of Martinez-Villaluenga et al. (2020). The total dietary fiber content in our samples was consistent with the range observed by Martinez-Villaluenga et al. (2020) and Zhang et al. (2022), although slightly lower than the values reported by Št'astná et al. (2019). These differences may be attributable to the varying pedo-climatic and cultivation conditions across the different studies, despite the use of similar varieties. However, present findings regarding macronutrient contents of quinoa grains appeared to be consistent even under different pedoclimatic conditions from those of the origin of quinoa, suggesting that they represent a species-specific trait rather than a cultivar-dependent variation. When compared with other widely used gluten-free ingredients, such as rice and maize, quinoa shows a significantly higher dietary fiber content: 2.5–3 times higher than maize, and 50–65 times higher than rice, which contains very low amounts of fiber. The dietary fiber content of quinoa, especially the insoluble fraction, is much higher than that of maize and rice, two GF alternatives commonly used for the

formulation of cereal-based GF products. This could help to increase the fiber intake in coeliac populations, which typically consume low-fiber gluten-free foods (Pellegrini and Agostoni, 2015). The ash contents of Regalona, Titicaca, and Vikinga were comparable to those reported by Craine and Murphy (2020) (3.11%), and Nowak et al. (2016) (mean 3.3%, range 2.0%–7.7%). Our results also indicated that Titicaca had a lower starch content than the range reported by Martínez-Villaluenga et al. (2020). Compared with Regalona and Vikinga, Titicaca also had the lowest starch content. This may be explained by Titicaca's higher dietary fiber content and the inverse relationship between the biosynthesis of fiber and starch from carbohydrate precursors. According to Nowak et al. (2016), the total available carbohydrate content (starch + sugars) of Titicaca grown in central Italy was 66.6%; however, this includes contributions from sugars. The starch content of 58.9% reported by Zhang et al. (2022) was more consistent with our findings.

It should be noted that the quinoa cultivars examined in the various studies differed. Additionally, in the study by Št'astná et al. (2019), the quinoa samples were purchased commercially and therefore had an unknown genetic background.

4.2 Minerals

The iron, zinc, and phosphorus contents of the flour of the three cultivars (Table 1) were within the ranges reported in the review by Martínez-Villaluenga et al. (2020). Similarly, compared with the review by Nowak et al. (2016), the iron and zinc concentrations in our samples fell within the reported ranges, while the phosphorus content was approximately half of the average value reported. A possible explanation for this discrepancy lies in the likely variability in soil phosphorus availability across the studies included in these reviews, which encompassed a wide range of pedoclimatic conditions. In our case, the quinoa samples were obtained from an experimental field characterized by a moderate level of Olsen phosphorus, and no phosphorus fertilizers were applied.

The magnesium concentrations in our samples corresponded to the lower end of the range described by Martínez-Villaluenga et al. (2020) (207–502 mg/100 g dry matter) based on the data in Nowak et al. (2016), while the copper concentrations (0.63–0.77 mg/100 g dry matter) were lower than those reported by both Martínez-Villaluenga et al. (2020) (1.0–9.5 mg/100 g dry matter) and Nowak et al. (2016) (5.7–9.5 mg/100 g dry matter).

The calcium contents of Vikinga (120 mg/100 g dry matter) and Regalona (140 mg/100 g dry matter) fell within the ranges reported by Martínez-Villaluenga et al. (2020) (27.5–148.7 mg/100 g dry matter) and Nowak et al. (2016) (28–149 mg/100 g dry matter), while Titicaca showed slightly higher levels (170 mg/100 g dry matter).

Overall, the mineral content of quinoa grains is influenced by both genetic factors and environmental conditions. Bhardwaj et al. (2023) reported considerable genetic variability in the zinc, copper, and magnesium contents among quinoa germplasm. In addition, mineral content is also affected by soil nutrient availability and fertilization practices (Nascimento et al., 2014). Compared with other commonly used gluten-free raw materials, such as maize and rice, quinoa exhibits significantly higher calcium, iron, copper, zinc, phosphorus, and magnesium contents. Given the common

nutritional deficiencies found in individuals with coeliac disease – particularly calcium and iron – incorporating quinoa into gluten-free products could improve their nutritional value, as also suggested by Ballester-Sánchez et al. (2019).

4.3 Amino acids

The amino acid compositions of the proteins in the three quinoa cultivars analyzed in our study were similar to those reported by Nowak et al. (2016), and Craine and Murphy (2020), except for methionine and tryptophan, which were slightly lower in our samples (1.8–2.0 vs. 2.17 g 100 g⁻¹ protein for Methionine, and 0.69–0.97 vs. 1.08 g 100 g⁻¹ protein for tryptophan).

The two most limiting amino acids in our quinoa samples were the same as those identified by Craine and Murphy (2020): lysine and leucine. However, it is important to highlight that the nutritional importance of these amino acids varies depending on the age group considered. Lysine is the most limiting amino acid for infants, and the low lysine content found in our study is consistent with the findings of Craine and Murphy (2020), who identified lysine as the most deficient amino acid in quinoa, followed by leucine. In contrast, when the nutritional requirements of adults are considered, our results differed more markedly from those of Craine and Murphy (2020), as our quinoa samples were found to be lower in leucine than in lysine. Lysine, leucine, and tryptophan were identified as the most limiting amino acids by Nowak et al. (2016), although in our case, tryptophan was not among the most limiting. The PS values, calculated for adults, were 73 (tryptophan) in Nowak et al. (2016), 75–77 (leucine) in our tests, and 84 (leucine) in Craine and Murphy (2020).

These differences can be partially attributed to the scope of the various studies: we tested three cultivars, whereas Craine and Murphy (2020) analyzed 100 cultivars, and Nowak et al. (2016) reviewed data from 27 published papers. The main factor probably lies in the high genetic variability among quinoa cultivars (Bhardwaj et al., 2023). According to these authors, methionine, leucine, and lysine show the greatest variability among the essential amino acids in quinoa germplasm.

Significant differences in the composition of storage globulins among four quinoa cultivars (Amarilla, Chadmo, Sajama, Nariño) were also reported by Burrieza et al. (2019).

According to Goma (2013) and Gonzalez et al. (2012), the essential amino acid content of quinoa is ultimately influenced by the overall protein content, which is in turn partly determined by the degree of nitrogen fertilization. However, it is difficult to compare our fertilization levels – well known and consistent across the three quinoa cultivars, because they were grown in the same experimental field – with those examined by Craine and Murphy (2020) or in the studies reviewed by Nowak et al. (2016), because fertilization rates were either not reported or too variable.

Although most studies have identified lysine, leucine, and tryptophan as the most limiting amino acids in quinoa, other limiting amino acids have occasionally been reported, such as the aromatic amino acids (Ruales and Nair, 1992) or methionine (Mahoney et al., 1975). Interestingly, Repo-Carrasco et al. (2003) reported the nutritional composition of the cultivar Amarilla de Marangani, and showed that no amino acids occurred at below the WHO/FAO requirements.

This variability in amino acid composition highlights the need for breeding programs aimed at improving the protein quality of quinoa.

Quinoa has a higher lysine content compared with other summer cereals such as rice and maize, because the main storage proteins in quinoa are albumins and globulins, whereas they are prolamins (low in lysine) in rice and maize (Motta et al., 2019). Notably, the globulins in quinoa are particularly rich in lysine (Burrieza et al., 2019).

An exhaustive assessment of protein quality, however, should also consider digestibility, determining protein digestibility or PDCAAS or DIAAS, which we did not do. This is a limitation of the study that must be considered when evaluating the protein value of quinoa.

4.4 Starch digestibility

Current dietary guidelines promote the consumption of food products rich in SDS and RS, due to their beneficial impact on glycemic response and overall metabolic health. In particular, it has been reported that SDS-containing foods can attenuate the postprandial glycemic response by promoting a more gradual release of glucose in both healthy individuals and those with impaired glucose tolerance (Chisbert et al., 2024; Miao et al., 2015). The RS fraction, on the other hand, not only contributes to glycemic control but also acts as a fermentable substrate in the colon, fostering beneficial modulation of the gut microbiota (Xong Xiong et al., 2021; Baptista et al., 2024). Accordingly, human studies and meta-analyses have shown that diets rich in SDS and/or RS are associated with reduced postprandial glycaemic excursions, improved glucose homeostasis, and a more stable insulin response. In controlled feeding trials, consumption of high-SDS foods resulted in lower or more stable postprandial glycaemia compared with low-SDS counterparts, supporting a mechanistic link between starch digestibility and metabolic response (Raghunathan et al., 2025).

Regarding the SDS and RDS fractions, all three cultivars showed a considerable amount of SDS on AvS (%). In particular, Regalona exhibited the lowest SDS/AvS ratio, whereas the other two cultivars slightly exceeded the 40% threshold, suggesting a potential role in reducing the postprandial glycemic response (EFSA, 2011a). The correlation between SDS/AvS and fiber content was not significant ($R^2 = 0.36$; $P = 0.590$). Concerning the RS fraction, the RS/TS ratio ranged from 6.1% in Titicaca to 7.5% in Vikinga. Although this proportion contributes to the overall fiber content of these cultivars, it is unlikely to exert a significant effect on postprandial glycemia, as such an effect has been suggested only for foods containing at least 14% RS relative to total starch (EFSA, 2011b). An in-depth analysis of starch bioaccessibility, and consequently its potential bioavailability, is essential due to the associated beneficial effects of a low glycemic index and reduced postprandial glycemia products consumption. These effects are particularly relevant for individuals with coeliac disease, but may also provide health effects for the general population (Peres et al., 2023). However, although *in vitro* starch digestion data can provide a valuable mechanistic insight, confirmation through well-designed human intervention studies is essential to validate the physiological relevance of SDS and RS contents for predicting postprandial responses in healthy adults.

5 Conclusion

The three quinoa cultivars analyzed in this study proved to be valid alternatives to both wheat flour and gluten-free raw materials such as corn and rice, compared with which they have a higher protein content (ranging from 18.1% to 18.4%), The high fiber content (10.2%–13.7%) and the low carbohydrate content (54.8%–59.4%) also suggest a low *in vivo* glycemic index, a parameter which, however, was not determined in this experiment. Quinoa is a promising ingredient for the formulation of gluten-free foods.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Author contributions

FR: Conceptualization, Methodology, Writing – review and editing. GG: Data curation, Formal Analysis, Methodology, Writing – original draft. MD: Conceptualization, Methodology, Writing – review and editing. MC: Formal Analysis, Writing – original draft. RD: Formal Analysis, Writing – original draft. DM: Formal Analysis, Writing – original draft. AF: Data curation, Writing – original draft. VT: Conceptualization, Methodology, Writing – review and editing.

Funding

The author(s) declared that financial support was received for this work and/or its publication. This research was supported by a grant from the Emilia-Romagna Region under the 2014-2020 Rural Development Programme, within the project “QUINOVATION: Quinoa (*Chenopodium quinoa* Willd.): a profitable and sustainable alternative for the production of low glycemic index gluten-free flour”.

Conflict of interest

The author(s) declared that this work was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

The author FR declared that they were an editorial board member of Frontiers at the time of submission. This had no impact on the peer review process and the final decision.

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