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# Nutritional Content, Phytochemical Composition, and Physicochemical Properties of Different Quinoa (*Chenopodium quinoa* Willd.) Seed Varieties

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**Keywords:** *Chenopodium quinoa* Willd | dietary diversity | phytochemicals | plant-based nutrients | sustainable crop

## ABSTRACT

**Background and Objectives:** Quinoa (*Chenopodium quinoa* Willd.) is a pseudocereal with documented benefits for human health. The macronutrient composition and phytochemical content of the grain are known to vary depending on the variety and the growing location. In this context, three varieties of quinoa seeds from the United Kingdom (UK) and Brazil (BR) were analyzed for their nutritional value and phytochemical content.

**Findings:** All three varieties had high protein content (Variety 1: 12.82% ± 0.08%, Variety 2: 12.79% ± 0.06%, Variety 3: 15.23% ± 0.29%) and a balanced amino acid profile. The UK varieties (1 and 2) showed higher content ($p < 0.001$) of insoluble fiber (mean: 5.61%) compared with the BR variety (4.34%). ICP–MS analysis indicated that all varieties were rich in manganese, phosphorus, iron, zinc, copper, potassium, and magnesium. Of a total of 158 phytochemicals analyzed with targeted LC–MS/MS, ferulic acid, vanillic acid, kaempferol, and quercetin were detected in the highest quantities.

**Conclusions:** Quinoa is a promising candidate crop to incorporate in the human diet and contributes toward dietary recommendations in terms of macronutrients and minerals. Varietal variations affect physical properties and seed suitability as a functional ingredient in food formulations.

**Significance and Novelty:** Diversification of the human diet is an essential step for promoting biodiversity and ensuring sustainability of food production.

## 1 | Introduction

Promoting nutrient diversity within the human diet translates to consumption of a wide range of nutrients from different food sources and supporting human health by advocating a balanced diet, to prevent disease and improve health. Furthermore, maintaining current dietary trends, which are highly dependent on animal-based nutrients, will further deplete natural resources and contribute to greenhouse gas emissions (Xu et al. 2021). Diversification of nutrients to include plant-based sources could therefore contribute toward meeting climate targets in addition to promoting health. It is essential, therefore,

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to study new sustainable and quality sources of nutrients (Alae-Carew et al. 2022).

Quinoa is a climate-resilient annual crop native to the Andean region of South America with a botanical identity distinct from common cereal plants. It is a dicotyledonous plant belonging to the Amaranthaceae family, the Chenopodiaceae sub family, and the Chenopodium genus and is often referred to as a pseudocereal (Contreras-Jiménez et al. 2019). Quinoa has been classified as a "future smart food" by the Food and Drug Administration (FAO) and 2013 was declared the "International year of Quinoa" (FAO 2018). The crop possesses agronomical traits, and therefore, quinoa farming can play a significant role in tackling food security challenges worldwide. The quinoa plant is highly resilient to environmental changes, including adverse climate and soil conditions, and is known to adapt to lands where cereal crops do not grow well (Jacobsen et al. 2003; Hussain et al. 2021). In recent-years, the cultivation of quinoa varieties in arid and semi-arid environments has expanded steadily, driven by the crop's resilience to harsh environmental conditions, thus highlighting its potential contribution toward tackling food security under changing climatic conditions (Semmar et al. 2025). This has led to a major increase in quinoa production from 80,069 metric tons in 2010 to 175,188 metric tons in 2020 (Shahbandeh 2022). The increasing popularity of quinoa production is also reflected in the shift of countries involved in cultivating the crop from the initial producers Peru, Bolivia, Ecuador, Argentina, Chile, and Colombia to more than 90 countries across the globe, including the United States, Canada, China, India, Finland, Australia, Kenya, the United Kingdom, Japan, and Brazil (Chaudhary et al. 2023; Bazile et al. 2016). According to the Quinoa Global Market Report (2025), the Quinoa market size is expected to witness rapid growth in the next few years. It will grow to $187.19 billion in 2029 at a compound annual growth rate (CAGR) of 10.6%.

In addition to the documented agronomic advantages of the crop, quinoa seed has exceptional nutritional properties that even more justify its exploitation as a valuable food ingredient. These are primarily owing to the seed's high protein content (~15%) with a favorable profile of essential amino acids, particularly lysine and methionine (Mota et al. 2016; Bhargava et al. 2007). The seed is a good source of fiber (~13%), predominantly of the insoluble type (cellulose and hemicellulose), while starch is the predominant carbohydrate (~55%–60%) (Lamothe et al. 2015; Tan et al. 2020). Quinoa seed is also known to be the source of compounds with documented benefits for human health, including vitamins B (i.e., folic acid), C, and E, unsaturated fatty acids (i.e., linoleic and linolenic acids), phytochemicals (i.e., flavonoids), and minerals such as calcium, phosphorus, iron, magnesium, potassium, manganese, and zinc (Abugoch et al. 2008). The outer layers (hull) of quinoa seed are rich in glycosidic compounds, namely, saponins, which has anti-nutritional properties and a bitter taste (Han et al. 2019). To improve the palatability of quinoa products, the seeds are often washed with water or subjected to a milling process to physically remove the saponin fraction (Ridout et al. 1991).

Quinoa is widely cultivated in many areas around the globe, and yet, the seed quality shows distinctive differences. Currently, approximately 250 *Chenopodium* species are cultivated around the world, which differ in chemical and nutritional compositions depending on the genetic diversity and growing locations (Pedrali et al. 2023). For instance, the amylose content of quinoa seed starch varies significantly, and the variation is largely attributed to the varieties and agronomical conditions in which the plant is cultivated (Lorenz 1990; Lindeboom et al. 2005). Furthermore, previous work indicates that the contents of proteins, carbohydrates, oxalic acid, γ-tocopherol, and total tocopherol were significantly different among differently colored quinoa varieties (Pereira et al. 2019). Genetic variability is likely to play a more prominent role than environmental and climatic factors in the nutritional profile, polyphenol content, and antioxidant capacity of quinoa seeds (Pedrali et al. 2023).

These compositional differences among quinoa varieties affect their physicochemical properties and determine their suitability for end-use food applications (Aluwi et al. 2017). Color seed variety and origin determine lipid, amino acid, and polyphenol contents of the crop, which in turn affect the textural properties of cooked quinoa (Feng et al. 2022). This suggests that the macronutrient, trace element, and phytochemical contents of the seed will vary significantly across varieties and growing locations. This may be due to variations in genetic and environmental factors, including soil conditions and climate. Quinoa varieties grown at low altitudes (2600 meters) in Peru showed higher water adsorption capacity compared with varieties grown at 3818 meters above sea level (Zapana-Yucra et al. 2025). These variations may affect the quality and handling properties (i.e., during milling) of quinoa seeds and quinoa-based products and can determine their applications in food formulations.

In this context, the present work aimed to analyze the nutritional and phytochemical content of three Quinoa (*Chenopodium quinoa* Willd.) varieties sourced from two distinct geographical locations: UK (two varieties) and BR (one variety). Both countries are not included in the list of primary producers of the crop and have introduced commercial quinoa cultivation since 1983 and 1989, respectively (Bazile et al. 2015). The objective of this study was to identify compositional differences between the UK and BR varieties and to characterize their nutritional and physical properties associated thereof. The results of this study provide meaningful insights for diversifying the utilization of quinoa seed as a valuable ingredient in food formulations in the context of a balanced and sustainable diet.

## 2 | Materials and Methods

### 2.1 | Materials

UK quinoa seeds (*Chenopodium quinoa* Willd.) Atlas (variety 1), known to be a saponin free variety, and Temuco (variety 2) were both obtained from The British Quinoa Company (Shropshire, England). Brazilian quinoa seeds (*Chenopodium quinoa* Willd.) BRS Piaburu (variety 3) were obtained from Harmony Bioseeds (Minas Gerais, Brazil). The quinoa seeds were subjected to freeze milling (Spex 6700 Edison, USA) and the samples were vacuum-packed and stored at −20°C before analysis.



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Standards and general laboratory reagents were purchased from Sigma-Aldrich (Gillingham, England) and Fisher Scientific UK Ltd. (Loughborough, England) or synthesized as described previously (Russell et al. 1996, 2003). The chemicals used for ICP–MS analysis were nitric acid of TraceSelect Ultra grade (Fluka, Sigma-Aldrich), hydrochloric acid (30%) of Ultrapur grade (Merck, Darmstadt, Germany), and deionized water (Millipore, Bedford, MA). Single element standards were purchased from all Inorganic Ventures (Christiansburg, USA).

## 2.2 | Nutritional Analysis

The protein content of the quinoa samples was analyzed based on the Dumas combustion method published previously (Buckee 1994). Protein was determined by measuring crude nitrogen using a Vario Max CN analyzer (Elementar; Stockport, England) and then multiplying the result by 6.25.

The total fat analysis of the quinoa samples was carried out based on a method published previously using the Soxtec method (Soxtec 2050 Auto Fat Extraction System) (Anderson 2004).

Dry matter and ash content of quinoa samples were determined according to the AOAC methods (AOAC 2005).

The soluble (SP) and insoluble nonstarch polysaccharide (NSP) and resistant starch content of the quinoa samples were determined according to the Englyst method (Englyst et al. 1992). The analysis of NSP sugars was performed by gas chromatography using a Hewlett Packard HP7890N chromatograph equipped with an SP2330 30 m × 0.75 mm column. The total carbohydrate content in the diet was determined following hydrolysis and available carbohydrates were broken down to their constituent monosaccharides. The released glucose is determined using a glucose oxidase procedure (Roe et al. 2015).

The micronutrient mineral content of quinoa samples was analyzed using inductively coupled plasma mass spectrometry (ICP–MS) as previously described (Multari et al. 2016). The following isotopes were analyzed: $^{23}$Na, $^{24}$Mg, $^{31}$P, $^{39}$K, $^{44}$Ca, $^{52}$Cr, $^{55}$Mn, $^{56}$Fe, $^{59}$Co, $^{63}$Cu, $^{66}$Zn, $^{78}$Se, $^{95}$Mo, and $^{111}$Cd using an Agilent 7700X spectrometer instrument (Agilent Technologies).

The amino acid content was assessed in the quinoa samples. Acid hydrolysis was performed for sample preparation before analysis for the following amino acids: histidine (His), serine (Ser), arginine (Arg), glycine (Gly), aspartic acid (Asp), glutamic acid (Glu), threonine (Thr), alanine (Ala), proline (Pro), lysine (Lys), tyrosine (Tyr), valine (Val), Isoleucine (ILeu), leucine (Leu), and phenylalanine (Phe). For the analysis of methionine (Met) and cysteine (Cys), the oxidation procedure was used. Sample preparation following the standardized methods used the acid hydrolysis method and the oxidation method (AOAC 2003). Tryptophan analysis was not performed on the quinoa samples.

For the analysis of amino acids, Waters application for Acquity by AccQ-Tag derivatization using Acquity (ultra-pressure liquid chromatography) UPLC (Waters Application, 2021) was employed. The AccQ-Tag method is a pre column derivatization technique for amino acids. The system, in combination with the AccQ-Tag Ultra method, enables the derivatization of amino acids, separation of the derivatives using reverse-phase UPLC, and quantification of the derivatives according to ultraviolet (UV) absorbance. For this analysis, an Accq-Tag ULTRA C18 1.7 μm, 2.1 × 100 mm column was used on an Acquity UPLC system, equipped with a TUV detector set at 260 nm, sample temperature 20°C. The flow was 0.7 mL min/min using a quaternary solvent system gradient over 10 min for the separation.

## 2.3 | Phytochemical Analysis

The quinoa samples were measured for derivatives and metabolites of simple phenols, benzoic acids, phenolic acids, phenylacetic acids, phenypropionic acids, phenylpyruvic acids, phenyllactic acids, mandellic acids, phenolic dimers, acetophenones, benzaldehydes, cinnamaldehydes, benzyl alcohols, cinnamyl alcohols, indoles, isoflavones, coumarins, chalcones, flavanones, flavones, anthocyanins, and flavonols.

A three-step extraction method was used for the extraction of phenolic compounds, generating three different fractions. Briefly, the samples were initially suspended in hydrochloric acid and extracted into ethyl acetate (Neacsu et al. 2013). This extraction was repeated three times, and the ethyl acetate extracts were combined, evaporated to dryness (representing the "free fraction"), and stored at −70°C before analysis by LC–MS/MS. The remaining aqueous fraction was first alkaline-hydrolyzed and then acid-hydrolyzed at room temperature for 4 h and, respectively, 30 min at 95°C and then the samples were extracted into ethyl acetate (pH 2) and processed as described above. The extracts obtained after alkaline and acid hydrolysis represent the "bound fractions."

For the LC–MS/MS analysis, methods published previously have been used (Neacsu et al. 2013; Russell and Duncan 2013; Neacsu et al. 2015). Liquid chromatography separation of the metabolites was performed on an Agilent 1100 LC–MS system (Agilent Technologies, Wokingham, UK) using a Zorbax Eclipse 5 μm, 150 mm × 4.6 mm C18 column (Agilent Technologies). Three distinct gradients were used to separate the different categories of metabolites and the mobile-phase solvents in each case were water containing 0.1% acetic acid and acetonitrile containing 0.1% acetic acid. The eluent was then directed without splitting into an ABI 3200 triple quadrupole mass spectrometer (Applied Biosystems, Warrington, UK) fitted with a Turbo Ion Spray (TIS) source. All the metabolites were quantified using multiple reaction monitoring (MRM). For all the phytochemical quantifications, standard calibration curves were prepared at concentration intervals of 2 ng/μL up to 10 pg/μL. The threshold used for quantification had a signal to noise ratio of 3 to 1. All the ion transitions for each of the metabolites were determined based on their molecular ions and strong fragment ions and their voltage parameters; declustering potential, collision energy, and cell entrance/exit potentials were optimized individually for each metabolite and have been previously described (Neacsu et al. 2013; Russell and Duncan 2013; Neacsu et al. 2015).

## 2.4 | Physical Properties

Moisture content was determined gravimetrically by placing 1.5 g of samples in a preweighed crucible and drying at 100°C in



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an oven overnight until a constant weight was reached (approx. 22 h). Crucibles were then cooled in a desiccator and reweighed. The loss of weight on drying was used to calculate the amount of moisture in powder using the formula

$$\text{Moisture content (\%)} = \frac{\text{Weight of water loss}}{\text{Weight of powder}} \times 100 \quad (1)$$

To determine water solubility, 1 g of powder was suspended onto the surface of 100 g of Milli-Q water at 25°C in a 500 mL beaker (diameter 80 mm). The mixture was then stirred continuously at 800 rpm for 7 min using a Cole Parmer digital stirrer. Samples were allowed to stand for 30 s before transferring 20 mL of the mixture into a centrifuge tube and were centrifuged for 10 min at 2900 *g*. Approximately 8–12 g of the supernatant was weighed and placed in a dry preweighed crucible and allowed to dry overnight to a constant weight at 100°C. Crucibles were cooled in a desiccator and reweighed. The solubility of the powders was calculated using the following equation:

$$\text{Solubility (\%)} = \frac{(100 + a) \times \%\text{TS}}{a \times (100 - b)/100} \quad (2)$$

where a is the amount of powder (g), b is the moisture content in the powder, and % TS is the percentage of dry matter in the supernatant.

Dispersibility was determined by placing 1 g of powder on the surface of 100 g of Milli-Q water at 25°C in a 500 mL beaker (diameter 80 mm). The mixture was stirred continuously at 800 rpm for 7 min (Cole Parmer digital stirrer), it was allowed to stand for 30 s, and then 20 mL of the mixture was transferred through a 60-mesh (~210 μ) sieve. Approximately 8–10 g of the filtrate was then transferred into a dry crucible and allowed to dry overnight to a constant weight at 100°C. Crucibles were cooled in a desiccator and reweighed. Dispersibility was calculated using the following equation:

$$\text{Dispersibility (\%)} = \frac{(100 + a) \times \%\text{TS}}{a \times (100 - b)/100} \quad (3)$$

where a is the amount of powder (g), b is the moisture content in the powder, and % TS is the percentage of dry matter in the supernatant.

A modified method of the static wetting test was used to determine wettability (Freudig et al. 1999). Briefly, 1 g of powder was sprinkled onto the surface of 100 g of Milli-Q water at 25°C in a 500 mL beaker (diameter 80 mm). Wettability was determined by visual observation and expressed as the time (sec) required for the powder to sink in the water.

Loose bulk density was determined by transferring 2 g of powder to a 10 mL measuring cylinder (without shaking or tapping the cylinder). The volume of powder was recorded and used in the calculation of loose bulk density. For tapped density determination, the above procedure was modified by tapping the cylinder on a rubber mat from a height of 15 cm for 120 or until constant volume was achieved; then, the volume of the powder was recorded. The loose and tapped bulk densities of the powders were calculated using the following equations:

$$\text{Loose bulk density} = \frac{\text{weight of powder (g)}}{\text{bulk powdered volume (cm}^3\text{)}} \quad (4)$$

$$\text{Tapped bulk density} = \frac{\text{weight of powder (g)}}{\text{tapped powdered volume (cm}^3\text{)}} \quad (5)$$

Water (WHC)- and oil (OHC)-holding capacities were determined by adding 1 g of powder to preweighed 50 mL plastic centrifuge tubes and adding 10 mL of distilled water or 20 mL of sunflower oil (density = 0.9 $g.mL^{-1}$), respectively, and mixing well for 30 s using a vortex at a high speed. Mixtures were allowed to stand at room temperature (22°C ± 2°C) for 30 min and then centrifuged at 1200 *g* for 30 min. The supernatant was carefully decanted, and the mass of the sample was recorded. Water- and oil-holding capacities were calculated using the following equations:

$$\text{WHC} = \frac{\text{weight of water (g)}}{\text{weight of powder (g)}} \quad (6)$$

$$\text{OHC} = \frac{\text{weight of oil (g)}}{\text{weight of powder (g)}} \quad (7)$$

A Konica Minolta CR1 10 color meter (Konica Minolta Solutions Ltd., Basildon, UK) was used to determine color properties. Measurements were made using the International Commission on Illumination (CIE) system, with L* representing lightness, a* representing red to green, and b* representing yellow to blue coordinates.

### 2.5 | Statistical Analysis

Nutritional data are reported as the means and standard errors (SEM) from at least triplicate measurements from each sample. Kolmogorov–Smirnov and Shapiro–Wilks tests were used to validate normality of the data. One-way analysis of variance (ANOVA) was conducted in version 27 of IBM SPSS (SPSS for Windows 22, SPSS Inc., Chicago, IL, USA) to identify differences among the concentrations of macronutrients, micronutrients, amino acids, and phytochemicals, and the physical properties of the flours. The Bonferroni post hoc test was used for analysis. Values of $p < 0.05$ were considered to be statistically significant. The phytochemicals' data are reported as the means and standard deviation of three technical replicates and the molecule profiles measured by LC–MS/MS were analyzed by principal component analysis (PCA), unit variance (UV)-scaled using SIMCA 14.1 (Umetrics, Cambridge, UK).



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## 3 | Results

### 3.1 | Nutritional Content

#### 3.1.1 | Proximate Composition

The results of the proximate analysis of the three quinoa varieties from two growing locations are presented in Table 1. Data revealed that the proximate composition was significantly affected by the variety and the growing location. The protein content was appreciably high for all three varieties (> 12%). Results indicate that variety 3 quinoa has significantly higher protein content ($p < 0.05$) than those grown in the UK (varieties 1 and 2). Fat content was the highest in variety 1 (6.19%), followed by varieties 2 (3.84%) and 3 (3.48%). The carbohydrate content in quinoa varieties, which is predominantly starch, ranged from 50.06% to 58.55%, with variety 2 showing a significantly lower ($p < 0.05$) value compared to varieties 1 and 3. The total fiber content, expressed as nonstarch polysaccharides (NSP), was the highest for variety 2 (5.81%) and the lowest for variety 3 (4.34%), whereas resistant starch was detected at low values (< 0.5%). Fiber content was predominantly comprised of insoluble NSP, with an average of 5.09%, and mainly contained arabinose, glucose, and uronic acid (Table 2). Dry matter and ash content were significantly different ($p < 0.05$) among the samples and averaged at 87.25% and 2.91%, respectively.

#### 3.1.2 | Element Composition

Element composition data of the three quinoa varieties are presented in Table 3. As indicated by the results, quinoa is a rich source of minerals and trace elements. In the present study, potassium content was the highest (average: 10,197.19 mg/Kg), followed by phosphorus (average: 5020.67 mg/Kg), magnesium (2226.00 mg/Kg), and calcium (743.75 mg/Kg), and the remaining elements (sodium, manganese, iron, copper, zinc, selenium) were detected in minor amounts. Significant differences ($p < 0.05$) were detected among samples, with variety 2 showing the highest content of potassium, phosphorus, magnesium, calcium, iron, manganese, and sodium. The variation observed may be due to varietal characteristics and other factors related to the growing environment such as soil and climate conditions.

#### 3.1.3 | Amino Acid Composition

The amino acid composition of the three quinoa varieties is presented in Table 4. Data indicated that all three varieties are sources of the nine essential amino acids. Data are in agreement with the protein content (Table 1) and confirmed that variety 3 has the highest content of total amino acids overall. The amino acid content of variety 3 is significantly higher ($p < 0.05$) than those of varieties 1 and 2 for the majority of amino acids, including His, Ser, Arg, Gly, Asp, Glu, Thr, Ala, Pro, Lys, Val, Ileu, Leu, and Met. Although varieties 1 and 2 showed similar amino acid contents ($p > 0.05$), variety 1 had a higher content than variety 2 for most of the amino acids listed, except for Ser, Asp, Glu, and Ala.

#### 3.1.4 | Phytochemical Composition

A total of 158 molecules were analyzed in the quinoa samples by targeted LC–MS/MS analysis, and the individual concentrations of these phytochemicals are presented in Table 5. Representatives of simple phenols, benzoic acids, phenolic acids, phenylacetic acids, phenypropionic acids, phenyl pyruvic acids, phenyllactic acids, mandellic acids, phenolic dimmers, acetophenones, benzaldehydes, cinnamaldehydes, benzyl alcohols, cinnamyl alcohols, indoles, isoflavones, coumarins, chalcones, flavanones, flavones, and flavonols were quantified in three different fractions extracted from quinoa samples, in free and bound forms (alkali- and acid-labile forms). Principal component analysis (PCA) analysis of the quinoa metabolites measured by LC–MS/MS (Figure 1A) shows a segregation between the forms in which the quinoa phytochemicals were extracted, with the free, alkali-labile, and acid-labile molecules being in different quadrants of the PCA plot. This indicates a similar profile of the molecules quantified in these different fractions extracted from all the quinoa varieties, rather than segregation between varieties. Quinoa variety 2 sourced from the UK had the highest amount of total phytochemicals compared with varieties 1 and 3, with a total of 4572.52 mg/kg indole 3-pyruvic acid, a protein degradation metabolite, accounting for most of this. More than half of the phytochemicals (2616.58 mg) were extracted in free form (Figure 1B). Furthermore, this variety also had the highest concentration of alkali-labile molecules (1091.4 mg) compared with varieties 1 and 3. The rest of the most abundant (measured in highest concentrations) phytochemicals analyzed (excluding

**TABLE 1** | Dry matter, ash, protein, total fat, total carbohydrates, total nonstarch polysaccharides, and resistant starch as % of fresh weight ($n = 3 \pm$ SEM) in the quinoa samples.

| Value (%) | Quinoa variety 1 | Quinoa variety 2 | Quinoa variety 3 | Overall ANOVA (*p* values) |
|---|---|---|---|---|
| Dry matter | 88.21 ± 0.04a | 85.94 ± 0.04b | 87.60 ± 0.02c | < 0.001 |
| Ash | 2.79 ± 0.02a | 3.69 ± 0.02b | 2.25 ± 0.04c | < 0.001 |
| Protein | 12.82 ± 0.08a | 12.79 ± 0.06a | 15.23 ± 0.29b | < 0.001 |
| Total fat | 6.19 ± 0.04a | 3.84 ± 0.03b | 3.48 ± 0.07c | < 0.001 |
| Total carbohydrates | 58.55 ± 0.72a | 50.06 ± 0.58b | 57.67 ± 0.94a | < 0.001 |
| Total NSP | 5.411 ± 0.122a | 5.812 ± 0.222a | 4.341 ± 0.174b | < 0.001 |
| Resistant starch | 0.41 ± 0.01a | 0.20 ± 0.00b | 0.50 ± 0.00c | < 0.001 |

*Note:* Different low case letters indicate significant differences between mean values for each variety ($p < 0.05$).



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**TABLE 2** | Monosaccharide composition (%) of soluble polysaccharide (SP) and insoluble nonstarch polysaccharide (NSP) content, expressed as mean ± SEM ($n = 3$).

| | Quinoa variety 1 | Quinoa variety 2 | Quinoa variety 3 | Overall ANOVA (*p* values) |
|---|---|---|---|---|
| Soluble NSP | | | | |
| Rhamnose | nd | nd | nd | — |
| Fucose | nd | nd | 0.005 ± 0.003 | — |
| Arabinose | nd | 0.007 ± 0.004 | 0.008 ± 0.003 | ns |
| Xylose | nd | nd | 0.007 ± 0.001 | — |
| Mannose | nd | nd | 0.003 ± 0.003 | — |
| Galactose | nd | 0.002 ± 0.002 | 0.003 ± 0.003 | ns |
| Glucose | nd | nd | 0.004 ± 0.004 | — |
| Uronic acid | 0.045 ± 0.003a | 0.088 ± 0.011b | 0.089 ± 0.003b | < 0.05 |
| Total soluble NSP | 0.045 ± 0.003a | 0.097 ± 0.016ab | 0.118 ± 0.017b | < 0.05 |
| Insoluble NSP | | | | |
| Rhamnose | 0.083 ± 0.003 | 0.099 ± 0.005 | 0.080 ± 0.007 | ns |
| Fucose | 0.040 ± 0.002 | 0.047 ± 0.004 | 0.044 ± 0.015 | ns |
| Arabinose | 1.384 ± 0.034a | 1.234 ± 0.070a | 0.786 ± 0.025b | < 0.001 |
| Xylose | 0.210 ± 0.001a | 0.228 ± 0.009a | 0.127 ± 0.007b | < 0.001 |
| Mannose | 0.102 ± 0.002a | 0.148 ± 0.003b | 0.067 ± 0.008c | < 0.001 |
| Galactose | 0.224 ± 0.006a | 0.308 ± 0.020b | 0.185 ± 0.011a | < 0.05 |
| Glucose | 1.852 ± 0.085ab | 2.042 ± 0.116a | 1.544 ± 0.035b | < 0.05 |
| Uronic acid | 1.471 ± 0.008ab | 1.612 ± 0.016a | 1.390 ± 0.061b | < 0.05 |
| Total insoluble NSP | 5.366 ± 0.119a | 5.718 ± 0.206a | 4.223 ± 0.157b | < 0.05 |

*Note:* Different low case letters indicate significant differences between mean values for each variety ($p < 0.05$).
Abbreviations: nd, not detected; ns, not significant.

**TABLE 3** | Main elements Na (sodium), Mg (magnesium), P (phosphorus), K (potassium), Ca (calcium), Mn (manganese), Fe (iron), Cu (copper), Zn (zinc), and Se (selenium) in quinoa samples expressed in mg/kg ± SEM ($n = 3$) analyzed by ICP–MS analysis.

| Element | Quinoa variety 1 | Quinoa variety 2 | Quinoa variety 3 | Overall ANOVA (*p* values) |
|---|---|---|---|---|
| Na | 1.48 ± 1.48a | 1.89 ± 0.96a | 1.44 ± 1.44a | ns |
| Mg | 2135.33 ± 30.99b | 2690.96 ± 19.14a | 1851.71 ± 148.39b | < 0.05 |
| P | 5398.57 ± 68.03a | 5705.79 ± 322.02a | 3957.67 ± 227.16b | < 0.05 |
| K | 9581.13 ± 46.89a | 13520.91 ± 714.76b | 7489.55 ± 404.6a | < 0.001 |
| Ca | 497.65 ± 7.65b | 1233.35 ± 66.11a | 500.27 ± 40.5b | < 0.001 |
| Mn | 26.82 ± 0.14b | 38.08 ± 0.35a | 25.42 ± 2.18b | < 0.05 |
| Fe | 47.09 ± 0.30a | 55.16 ± 1.19a | 50.34 ± 3.16a | ns |
| Cu | 7.67 ± 0.08a | 5.27 ± 0.07b | 6.23 ± 0.35b | < 0.05 |
| Zn | 28.94 ± 0.1b | 35.25 ± 0.41ab | 41.59 ± 2.48a | < 0.05 |
| Se | 0.06 ± 0.00a | 0.01 ± 0.00b | 0.01 ± 0.00b | < 0.001 |

*Note:* Different lower case letters indicate significant differences between mean values for each variety ($p < 0.05$).
Abbreviation: ns, not significant.

indole 3-pyruvic acid) are shown in Figure 1C,D, suggesting a similar profile across the quinoa varieties analyzed. Ferulic acid was the next most abundant molecule found in all of the quinoa varieties and mainly extracted following alkaline extraction. Vanillic acid was also abundant in quinoa, found mainly in the bound form and released after both alkaline and acid hydrolysis. These results indicate mainly a quantitative rather than a qualitative difference in the phytochemicals profile of the quinoa varieties analyzed.

The following phytochemicals were not detected or were below the detection limit in all of the quinoa samples analyzed: m-hydroxybenzoic acid; 3,5-dihydroxybenzoic acid; o-anisic acid; m-anisic acid; 3,4,5-trihydroxybenzaldehyde; isovanillin; 3-methoxy



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**TABLE 4** | Amino acid composition of quinoa samples as mean µmoles/g sample ± SEM ($n = 3$).

| Amino acid | Quinoa variety 1 | Quinoa variety 2 | Quinoa variety 3 | Overall ANOVA (*p* values) |
|---|---|---|---|---|
| His | 39.39 ± 2.72ab | 34.61 ± 3.92a | 46.15 ± 2.21b | < 0.05 |
| Ser | 83.71 ± 2.59a | 84.95 ± 2.38a | 93.81 ± 1.37b | < 0.05 |
| Arg | 102.23 ± 5.51a | 99.1 ± 9.32a | 139.02 ± 5.70b | < 0.05 |
| Gly | 150.58 ± 2.87a | 148.03 ± 5.8a | 172.78 ± 2.47b | < 0.001 |
| Asp | 66.35 ± 2.71a | 74.00 ± 6.05a | 89.76 ± 3.91b | < 0.05 |
| Glu | 101.38 ± 4.81a | 111.96 ± 7.23a | 141.81 ± 10.60chb | < 0.05 |
| Thr | 59.56 ± 2.68ab | 55.1 ± 4.79a | 65.36 ± 1.21b | < 0.05 |
| Ala | 63.54 ± 3.38a | 65.29 ± 0.87a | 76.99 ± 3.81b | < 0.05 |
| Pro | 52.77 ± 1.75a | 52.67 ± 1.71a | 61.87 ± 1.68b | < 0.05 |
| Lys | 41.09 ± 4.06a | 39.36 ± 2.15a | 50.89 ± 3.86b | < 0.05 |
| Tyr | 36.26 ± 2.95a | 32.33 ± 2.78a | 38.37 ± 3.05a | ns |
| Val | 50.39 ± 8.07ab | 46.3 ± 10.27a | 70.43 ± 2.05b | < 0.05 |
| Ileu | 35.5 ± 6.01a | 33.16 ± 8.71a | 52.18 ± 1.51b | < 0.05 |
| Leu | 77.6 ± 4.06a | 74.3 ± 5.48a | 94.36 ± 1.69b | < 0.05 |
| Phe | 53.33 ± 4.61a | 48.11 ± 6.31a | 60.49 ± 3.77a | ns |
| Cys | 39.68 ± 0.30a | 38.96 ± 3.55a | 44.31 ± 2.70a | ns |
| Met | 24.02 ± 1.12ab | 20.78 ± 2.08a | 25.28 ± 0.99b | < 0.05 |

*Note:* Different lower case letters indicate significant differences between mean values for each variety ($p < 0.05$).
Abbreviations: ns, not significant.

benzaldehyde; 3,4-dimethoxybenzaldehyde; 3,4,5-trimethoxy benzaldehyde; o-coumaric acid; m-coumaric acid; 3-methoxy cinnamic acid; 4-methoxycinnamic acid; 3,4-dimethoxycinnamic acid; 3,4,5-trimethoxycinnamic acid; phenylpropionic acid; 2-hydroxyphenylpropionic acid; 3-hydroxyphenylpropionic acid; 4-hydroxyphenylpropionic acid; 3,4-dihydroxyphenylpropionic acid; 3-methoxyphenylpropionic acid; 1,2-hydroxybenzene; 1,3-hydroxybenzene; 1,2,3-trihydroxybenzene; 3,4-dimethoxyaceto phenone; 3,4,5-trimethoxyacetophenone; 3-hydroxyphenylacetic acid; 3,4-dihydroxyphenylacetic acid; 4-hydroxy-3-methoxyphenyl acetic acid; 4-methoxyphenylacetic acid; mandelic acid; 3-hydroxy mandelic acid; 4-hydroxymandelic acid; 4-hydroxy-3-methoxy mandelic acid; quinadilic acid; o-hydroxyhippuric acid; ethylferulate; p-cresol; 4-ethylphenol; 4-methylcatechol; ellagic acid; ferulic dimer (8–8 linked); ferulic dimer (5–5 hydrogenated); reservatrol; indole-3-acrylic acid; indole-3-propionic acid; indole-3-carbinol; indole-3-methyl; psoralen; 8-methylpsoralen; bergapten; coumesterol; catechin; epicatechin; gallocatechin; epigallocatechin; epigallocatechin gallate; 4-methylumbelliferone; 7-hydroxy-4-methyl coumarin; 4-hydroxy-6-methyl coumarin; luteolinidin; 2-hydroxy benzyl alcohol; 4-hydroxy-3-methoxycinnamyl alcohol; secoisolariciresinol; matairesinol; enterodiol; enterolactone; pinoresinol; lariciresinol; hydroxymatairesinol; 3-Indoleacetonitrile; isoliquiriti genin; phloretin; naringin; hesperitin; morin; genstein; umbelliferone; neohesperidin; quercitrin; poncirin; didymin; phloridzin; daidzein; equol; neoeriocitrin; gossypin; tyrosol; and hydroxytyrosol.

#### 3.1.5 | Physical Properties

The physical properties of food powders depend on the genetic and environmental factors of the seed and can be used to identify differences between varieties of the same species (Hadjichristodoulou 1990). Furthermore, data on physical properties can be used to determine storage and handling conditions and, as such, can influence consumer acceptability and the market value of the product. Table 6 presents the physical properties of the UK and BR quinoa flours. The varieties showed significant variations ($p < 0.05$) in their physical properties.

Moisture levels of powdered ingredients play a significant role in determining the shelf-life of food products and should be maintained at low levels (ideally < 6%) to limit the ability of water to act as a plasticizer and thus inhibit undesirable agglomeration of wet particles and prevent caking during storage (Santana et al. 2017). Moisture levels were relatively low for all samples (average 7.75%) but slightly higher in the UK sample (variety 1); however, no statistical significance was detected between the UK and BR cultivars. Loose bulk density determines the choice of the container size and strength of the reconstituted food, thus affecting storage and reconstitution properties of the powder. Low density of food powders is undesirable from a manufacturer's perspective, as it leads to higher costs of packaging and transportation (Schuck and Ouest 2011). On the other hand, depending on the desired properties of the final product, low bulk density may be beneficial. For instance, reconstituted foods from powders with low bulk density show low paste thickness and viscosity and are suitable for weaning foods (Beniwal et al. 2019). The BR sample (variety 3) had significantly higher density (loose bulk density and tapped bulk density) than the UK cultivar including both samples (varieties 1 and 2).

In terms of reconstitution properties, short wetting time and high dispersibility and solubility are crucial steps in the process



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**TABLE 5** | Phytochemical concentrations (mg/kg) measured in quinoa samples using LC–MS/MS analysis in free form and alkali- and acid-bound forms as mean ± SEM, $n = 3$.

| | Quinoa variety 1 | | | Quinoa variety 2 | | | Quinoa variety 3 | | |
|---|---|---|---|---|---|---|---|---|---|
| **Phytochemical** | **Free** | **Alkali-labile** | **Acid-labile** | **Free** | **Alkali-labile** | **Acid-labile** | **Free** | **Alkali-labile** | **Acid-labile** |
| Benzoic acid | 1.39 ± 0.09 | 1.02 ± 0.11 | 0.84 ± 0.36 | 2.19 ± 0.04 | 2.45 ± 0.06 | 1.89 ± 0.23 | 1.47 ± 0.05 | 1.46 ± 0.15 | 1.42 ± 0.86 |
| Salicylic acid | 0.33 ± 0.02 | 0.14 ± 0.02 | 0.23 ± 0.07 | 0.54 ± 0.09 | 0.22 ± 0.04 | 0.21 ± 0.01 | 0.43 ± 0.03 | 0.09 ± 0.03 | 0.2 ± 0.08 |
| p-hydroxybenzoic acid | 2.24 ± 0.14 | 7.16 ± 1.08 | 6.23 ± 1.32 | 2.95 ± 0.69 | 5.01 ± 0.17 | 1.69 ± 0.23 | 12.85 ± 1.14 | 4.02 ± 0.53 | 2.45 ± 0.31 |
| 2,3-dihydroxybenzoic acid | 0 ± 0 | 0 ± 0 | 0.03 ± 0 | 0.03 ± 0 | 0 ± 0 | 0.02 ± 0 | 0.04 ± 0 | 0 ± 0 | 0 ± 0 |
| 2,4-dihydroxybenzoic acid | 0 ± 0 | 0.09 ± 0.01 | 0.11 ± 0.03 | 0.04 ± 0.01 | 0.06 ± 0 | 0 ± 0 | 0.07 ± 0.01 | 0.05 ± 0.01 | 0.05 ± 0.02 |
| 2,5-dihydroxybenzoic acid | 0.47 ± 0.04 | 0.11 ± 0.04 | 1.34 ± 0.37 | 2.63 ± 0.66 | 0 ± 0 | 1.61 ± 0.15 | 2.51 ± 0.27 | 0 ± 0 | 0.53 ± 0.07 |
| 2,6-dihydroxybenzoic acid | 0.22 ± 0 | 0.01 ± 0.02 | 0 ± 0 | 0.09 ± 0.04 | 0 ± 0 | 0 ± 0 | 0.16 ± 0.05 | 0 ± 0 | 0 ± 0 |
| Protocatechuic acid | 0.11 ± 0.01 | 0.99 ± 0.26 | 7.35 ± 1.12 | 0.28 ± 0.05 | 2.74 ± 0.07 | 4.22 ± 0.81 | 1.15 ± 0.07 | 0.34 ± 0.07 | 4.35 ± 1.06 |
| p-anisic acid | 0.08 ± 0.01 | 0.17 ± 0.03 | 0.27 ± 0.08 | 0.08 ± 0.02 | 0.2 ± 0 | 0.25 ± 0.04 | 0.09 ± 0.01 | 0.14 ± 0.03 | 0.34 ± 0.1 |
| Gallic acid | 0 ± 0 | 0.02 ± 0.04 | 0 ± 0 | 0 ± 0 | 0.03 ± 0.04 | 0.04 ± 0.01 | 0 ± 0 | 0 ± 0 | 0 ± 0 |
| Vanillic acid | 6.86 ± 0.51 | 29.15 ± 3.68 | 38.51 ± 9.35 | 13.13 ± 3.13 | 20.37 ± 0.73 | 10.79 ± 1.18 | 26.35 ± 2.85 | 16.36 ± 2.35 | 16.21 ± 0.83 |
| Syringic acid | 0.21 ± 0.02 | 0.38 ± 0.05 | 0.77 ± 0.2 | 0.89 ± 0.22 | 0.72 ± 0.04 | 1 ± 0.07 | 0.67 ± 0.09 | 0.14 ± 0.02 | 0.28 ± 0.06 |
| 3,4-dimethoxybenzoic acid | 0 ± 0 | 0.37 ± 0.05 | 0 ± 0 | 0.17 ± 0.03 | 0.46 ± 0.02 | 0 ± 0 | 0.16 ± 0.03 | 0.16 ± 0.01 | 0 ± 0 |
| p-hydroxybenzaldehyde | 0.06 ± 0.01 | 0.54 ± 0.05 | 0.23 ± 0.07 | 0.03 ± 0.05 | 1.16 ± 0.2 | 0.25 ± 0.08 | 0.3 ± 0.01 | 1.09 ± 0.16 | 0.24 ± 0.01 |
| Protocatachaldehyde | 0 ± 0 | 0.1 ± 0.01 | 0.08 ± 0.01 | 0.02 ± 0.03 | 0.39 ± 0.05 | 0.18 ± 0.05 | 0.03 ± 0.01 | 0.1 ± 0.03 | 0.05 ± 0.01 |
| Vanillin | 0.1 ± 0.01 | 0.36 ± 0.09 | 0.33 ± 0.12 | 0.28 ± 0.02 | 2.16 ± 0.17 | 0.8 ± 0.19 | 0.19 ± 0.02 | 0.5 ± 0.07 | 0.22 ± 0.03 |
| Syringin | 0.04 ± 0 | 0.13 ± 0.03 | 0.17 ± 0.04 | 0.16 ± 0.02 | 0.36 ± 0.02 | 0.3 ± 0.02 | 0.09 ± 0.02 | 0.11 ± 0.02 | 0.11 ± 0.03 |
| Cinnamic acid | 1.65 ± 0.13 | 0.45 ± 0.09 | 0.15 ± 0.06 | 1.81 ± 0.31 | 0.49 ± 0.01 | 0.19 ± 0.05 | 1.66 ± 0.18 | 0.06 ± 0.01 | 0.02 ± 0.02 |
| p-coumaric acid | 0.27 ± 0.02 | 2.17 ± 0.33 | 0.09 ± 0.02 | 1.78 ± 0.4 | 2.67 ± 0.11 | 0.24 ± 0.09 | 12.18 ± 0.52 | 4.62 ± 0.57 | 0.22 ± 0.07 |
| Caffeic acid | 0.07 ± 0.01 | 0.35 ± 0.1 | 0.1 ± 0.02 | 0.14 ± 0.02 | 0.88 ± 0.12 | 0.18 ± 0 | 0.25 ± 0.02 | 0.37 ± 0.11 | 0.05 ± 0.01 |
| Ferulic acid | 4.59 ± 0.35 | 79.91 ± 11.01 | 1.92 ± 0.3 | 11.23 ± 2.57 | 76.43 ± 2.95 | 4.37 ± 1.23 | 12.48 ± 1.25 | 50.44 ± 7.21 | 1.68 ± 0.82 |
| Sinapic acid | 0.26 ± 0.03 | 2.1 ± 0.32 | 0.22 ± 0.02 | 0.86 ± 0.2 | 6.25 ± 0.52 | 0.44 ± 0.07 | 0.58 ± 0.06 | 1.5 ± 0.14 | 0.11 ± 0.06 |
| 4-hydroxy-3-methoxyphenylpropionic acid | 0.01 ± 0.02 | 0.05 ± 0 | 0.29 ± 0.06 | 0.11 ± 0.03 | 0.04 ± 0.01 | 0.22 ± 0.02 | 0.19 ± 0.02 | 0.05 ± 0 | 0.11 ± 0.07 |
| Phenol | 0 ± 0 | 1.61 ± 2.78 | 0 ± 0 | 0 ± 0 | 0 ± 0 | 0 ± 0 | 0 ± 0 | 0 ± 0 | 0 ± 0 |
| 4-hydroxyacetophenone | 0 ± 0 | 0.05 ± 0.01 | 0.05 ± 0.01 | 0 ± 0 | 0.04 ± 0 | 0.05 ± 0 | 0.14 ± 0.01 | 0.1 ± 0.01 | 0.06 ± 0 |
| 4-hydroxy-3-methoxyacetophenone | 0.01 ± 0.02 | 0.09 ± 0.01 | 0.33 ± 0.12 | 0.06 ± 0.02 | 0.2 ± 0.02 | 0.37 ± 0.06 | 0.07 ± 0.02 | 0.09 ± 0.01 | 0.12 ± 0.01 |

(Continues)



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TABLE 5 | (Continued)

| Phytochemical | Quinoa variety 1 | | | Quinoa variety 2 | | | Quinoa variety 3 | | |
|---|---|---|---|---|---|---|---|---|---|
| | Free | Alkali-labile | Acid-labile | Free | Alkali-labile | Acid-labile | Free | Alkali-labile | Acid-labile |
| 4-hydroxy-3,5-dimethoxyacetophenone | 0 ± 0 | 0 ± 0 | 0 ± 0 | 0.07 ± 0.02 | 0 ± 0 | 0.05 ± 0.01 | 0 ± 0 | 0 ± 0 | 0 ± 0 |
| Phenylacetic acid | 0.23 ± 0.02 | 0.03 ± 0.05 | 0 ± 0 | 0.8 ± 0.13 | 0.11 ± 0 | 0.06 ± 0.01 | 0.59 ± 0.07 | 0.03 ± 0.03 | 0 ± 0 |
| 4-hydroxyphenylacetic acid | 0 ± 0 | 0 ± 0 | 0.73 ± 0.13 | 0.46 ± 0.15 | 0 ± 0 | 0.48 ± 0.18 | 0.71 ± 0.17 | 0 ± 0 | 0.28 ± 0.08 |
| 3,4-dihydroxymandelic acid | 0 ± 0 | 0.02 ± 0.03 | 0 ± 0 | 0.02 ± 0.03 | 0.02 ± 0.03 | 0 ± 0 | 0.09 ± 0.01 | 0.05 ± 0.01 | 0 ± 0 |
| Phenylpyruvic acid | 0 ± 0 | 0.04 ± 0.04 | 0.19 ± 0.05 | 0.09 ± 0.01 | 0.1 ± 0.02 | 0.21 ± 0.05 | 0.2 ± 0.04 | 0.07 ± 0.01 | 0.1 ± 0.02 |
| 4-hydroxyphenylpyruvic acid | 7.68 ± 1.17 | 4.34 ± 0.85 | 3.26 ± 0.64 | 42.87 ± 17.59 | 4.72 ± 1.51 | 3.85 ± 0.1 | 11.05 ± 0.99 | 3.71 ± 0.51 | 8.96 ± 2.12 |
| Phenyllactic acid | 0.1 ± 0.01 | 0.04 ± 0.01 | 0 ± 0 | 0.18 ± 0.03 | 0.04 ± 0.01 | 0.03 ± 0 | 0.41 ± 0.05 | 0.04 ± 0 | 0.05 ± 0 |
| 4-hydroxyphenyllactic acid | 0.05 ± 0.01 | 0.03 ± 0.03 | 0.39 ± 0.05 | 0.15 ± 0.01 | 0.05 ± 0.01 | 0.25 ± 0.03 | 0.26 ± 0.04 | 0.06 ± 0.01 | 0.25 ± 0.16 |
| Anthranilic acid | 0.02 ± 0 | 0.27 ± 0.11 | 0.03 ± 0.01 | 0.1 ± 0.01 | 0.47 ± 0.08 | 0.13 ± 0.01 | 0.06 ± 0.01 | 0.2 ± 0.03 | 0.02 ± 0 |
| Chlorogenic acid | 0 ± 0 | 0.01 ± 0.01 | 0 ± 0 | 0.04 ± 0.01 | 0.03 ± 0.01 | 0 ± 0 | 0.19 ± 0.02 | 0.02 ± 0.01 | 0 ± 0 |
| Coniferyl alcohol | 0 ± 0 | 0 ± 0 | 0.31 ± 0.21 | 0 ± 0 | 0 ± 0 | 0.29 ± 0.08 | 0 ± 0 | 0 ± 0 | 0.67 ± 0.35 |
| Ferulic dimer (5–5 linked) | 0.02 ± 0 | 2.51 ± 0.28 | 0.04 ± 0 | 0 ± 0 | 2 ± 0.1 | 0.13 ± 0.02 | 0.02 ± 0 | 1.2 ± 0.22 | 0.04 ± 0.02 |
| Ferulic dimer (8–5 linked) | 0 ± 0 | 5.25 ± 0.51 | 0.38 ± 0.04 | 0 ± 0 | 3.16 ± 0.03 | 0.93 ± 0.22 | 0 ± 0 | 2.62 ± 0.39 | 0.42 ± 0.06 |
| Indole | 0.03 ± 0 | 0.12 ± 0.02 | 0 ± 0 | 0.11 ± 0 | 0.2 ± 0 | 0 ± 0 | 0.08 ± 0.01 | 0.1 ± 0.01 | 0 ± 0 |
| Indole-3-acetic acid | 0 ± 0 | 0 ± 0 | 0 ± 0 | 0.04 ± 0.05 | 0.06 ± 0.09 | 0 ± 0 | 0.11 ± 0.01 | 0 ± 0 | 0 ± 0 |
| Indole-3-carboxylic acid | 0.25 ± 0.02 | 0.26 ± 0.05 | 0 ± 0 | 0.56 ± 0.13 | 0.22 ± 0.02 | 0 ± 0 | 0.26 ± 0.02 | 0.08 ± 0.02 | 0 ± 0 |
| Indole-3-pyruvic acid | 370.17 ± 19.69 | 521.78 ± 183.91 | 894.38 ± 208.39 | 2516.49 ± 72.71 | 952.96 ± 35.1 | 796.85 ± 33.95 | 1012.79 ± 155.56 | 460.5 ± 103.05 | 680.01 ± 92.2 |
| Indoe-3-lactic acid | 0.01 ± 0 | 0 ± 0 | 0 ± 0 | 0.01 ± 0 | 0 ± 0 | 0 ± 0 | 0.02 ± 0.01 | 0 ± 0 | 0 ± 0 |
| Coumarin | 0 ± 0 | 0 ± 0 | 0 ± 0 | 0 ± 0 | 0.02 ± 0 | 0.01 ± 0.01 | 0 ± 0 | 0 ± 0 | 0 ± 0 |
| Tangeretin | 0 ± 0 | 0 ± 0 | 0 ± 0 | 0 ± 0 | 0 ± 0 | 0 ± 0 | 0 ± 0 | 0 ± 0 | 0.03 ± 0.02 |
| Imperatorin | 0 ± 0 | 0 ± 0 | 0 ± 0 | 0 ± 0 | 0 ± 0 | 0 ± 0 | 0 ± 0 | 0 ± 0 | 0.01 ± 0.01 |
| Glycitein | 0 ± 0 | 0 ± 0 | 0 ± 0 | 0.14 ± 0.01 | 0 ± 0 | 0 ± 0 | 0 ± 0 | 0 ± 0 | 0 ± 0 |
| Syringaresinol | 0 ± 0 | 0 ± 0 | 0 ± 0 | 7.55 ± 0.69 | 2.4 ± 0.23 | 0 ± 0 | 1.48 ± 0.17 | 0 ± 0 | 0 ± 0 |
| Indole 3-carboxaldehyde | 0.04 ± 0 | 0.18 ± 0.03 | 0 ± 0 | 0.16 ± 0.02 | 0.3 ± 0.01 | 0.01 ± 0 | 0.12 ± 0.01 | 0.15 ± 0.01 | 0 ± 0 |
| Kaempferol | 2.78 ± 0.09 | 0.23 ± 0.04 | 28.16 ± 2.56 | 0.78 ± 0.69 | 0.06 ± 0.05 | 9.87 ± 8.6 | 0.94 ± 0.31 | 0.11 ± 0.01 | 9.56 ± 4.41 |
| Quercetin | 4.37 ± 0.24 | 0.46 ± 0.07 | 24.09 ± 3.56 | 5.04 ± 4.38 | 0.13 ± 0.12 | 19.6 ± 17.04 | 7.76 ± 3.34 | 0.3 ± 0.05 | 20.96 ± 11.05 |
| Eriocitrin | 0 ± 0 | 0.04 ± 0.01 | 0 ± 0 | 0 ± 0 | 0.08 ± 0.07 | 0 ± 0 | 0 ± 0 | 0.06 ± 0.02 | 0 ± 0 |
| Naringenin | 0.06 ± 0.01 | 0.01 ± 0 | 0 ± 0 | 0.04 ± 0.04 | 0 ± 0 | 0.02 ± 0.02 | 0.1 ± 0.02 | 0 ± 0 | 0 ± 0.01 |

(Continues)



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**TABLE 5** | (Continued)

| Phytochemical | Quinoa variety 1 | | | Quinoa variety 2 | | | Quinoa variety 3 | | |
|---|---|---|---|---|---|---|---|---|---|
| | Free | Alkali-labile | Acid-labile | Free | Alkali-labile | Acid-labile | Free | Alkali-labile | Acid-labile |
| Myricetin | 0.01 ± 0.01 | 0 ± 0 | 0 ± 0 | 0 ± 0 | 0 ± 0 | 0 ± 0 | 0 ± 0 | 0 ± 0 | 0 ± 0 |
| Quercetin-3-glucoside | 0 ± 0 | 0.57 ± 0.08 | 0 ± 0 | 0 ± 0 | 0.78 ± 0.73 | 0 ± 0 | 0 ± 0 | 0.56 ± 0.06 | 0 ± 0 |
| Taxifolin | 0.02 ± 0 | 0 ± 0 | 0 ± 0 | 0.02 ± 0.01 | 0.02 ± 0.03 | 0.02 ± 0.02 | 0.05 ± 0.01 | 0 ± 0 | 0.01 ± 0.01 |
| Scopoletin | 0.01 ± 0 | 0 ± 0 | 0.02 ± 0.01 | 0.02 ± 0.02 | 0 ± 0 | 0.03 ± 0.03 | 0.01 ± 0 | 0 ± 0 | 0 ± 0 |
| 7,8-dihydroxy-6-methyl coumarin | 0 ± 0 | 0 ± 0 | 0 ± 0 | 0 ± 0 | 0 ± 0 | 0 ± 0 | 0 ± 0 | 0 ± 0 | 0 ± 0 |
| Hesperidin | 0 ± 0 | 0.04 ± 0.07 | 0 ± 0 | 0 ± 0 | 0 ± 0 | 0 ± 0 | 0 ± 0 | 0 ± 0 | 0 ± 0 |
| Biochanin A | 0.29 ± 0.01 | 0.04 ± 0.01 | 0.04 ± 0.01 | 0.26 ± 0.23 | 0.03 ± 0.03 | 0.08 ± 0.07 | 0.17 ± 0.04 | 0.02 ± 0.01 | 0.01 ± 0 |
| Galangin | 0.03 ± 0.03 | 0 ± 0 | 0 ± 0 | 0 ± 0 | 0 ± 0 | 0 ± 0 | 0 ± 0 | 0 ± 0 | 0 ± 0 |
| Luteolin | 0.02 ± 0 | 0 ± 0 | 0 ± 0 | 0.01 ± 0.01 | 0 ± 0 | 0 ± 0 | 0.02 ± 0 | 0 ± 0 | 0 ± 0 |
| Fisetin | 0.03 ± 0.01 | 0 ± 0 | 0 ± 0 | 0.01 ± 0 | 0 ± 0 | 0 ± 0 | 0 ± 0 | 0 ± 0 | 0 ± 0 |
| Formononetin | 0.02 ± 0.01 | 0 ± 0 | 0.01 ± 0.01 | 0.16 ± 0.27 | 0.01 ± 0.01 | 0.01 ± 0.01 | 0.02 ± 0.02 | 0.01 ± 0.01 | 0.01 ± 0.01 |
| Apigenin | 0.01 ± 0.01 | 0 ± 0 | 0 ± 0 | 0.01 ± 0.01 | 0 ± 0 | 0 ± 0 | 0 ± 0 | 0 ± 0 | 0 ± 0 |
| Isorhamnetin | 0.58 ± 0.15 | 0.07 ± 0.01 | 3.13 ± 0.22 | 0.9 ± 0.79 | 0.04 ± 0.03 | 2.37 ± 2.05 | 0.91 ± 0.37 | 0.02 ± 0 | 2.67 ± 1.54 |



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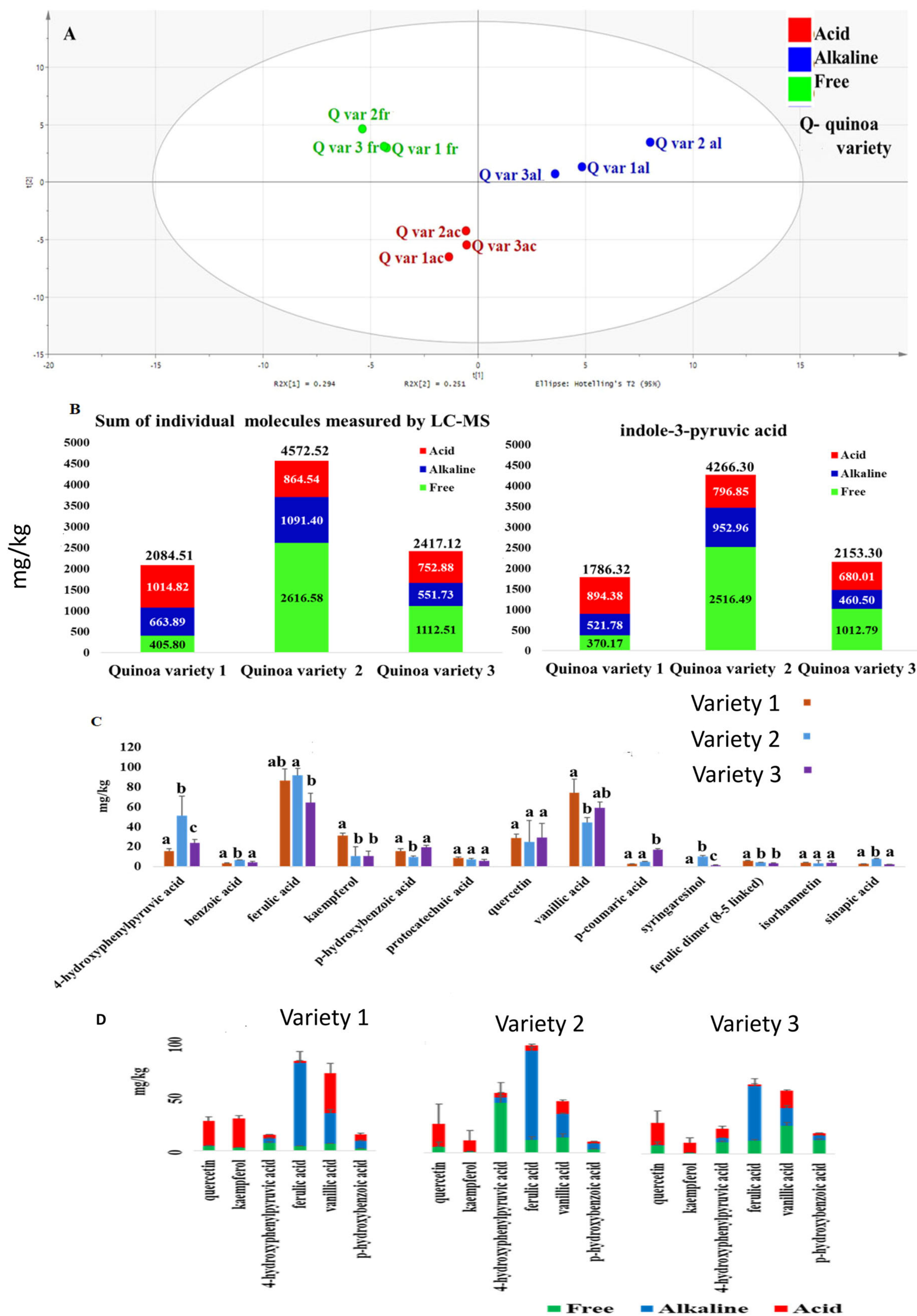


**FIGURE 1** | Phytochemical composition of the quinoa samples: (A) Principal component analysis (PCA) of all plant metabolites measured by LC–MS/MS in free and bound (acid and alkaline) fractions from quinoa samples. (B) Total phytochemical (free and acid- and alkali-bound) content (in mg/kg) obtained by summing the 158 individual plant metabolites measured by LC–MS/MS. (C) Most abundant molecules (mg/kg), (as mean ± SD, $n = 3$ summing the bound and free extractable molecules) measured in the quinoa samples, where a–c denote significant differences between quinoa samples. (D) Six most abundant phytochemicals measured in each of the quinoa samples (mg/kg) in free from, and acid- and alkali-bound forms (as mean ± SD, $n = 3$).

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TABLE 6 | Physical properties of quinoa samples expressed as mean ± SEM ($n = 3$).

| Quinoa variety | Moisture (%) | Loose bulk density (g/mL) | Tapped bulk density (g/mL) | Wettability (s) | Dispersibility (%) | Solubility (%) | Water-holding capacity (%) | Oil-holding capacity (%) | Color values | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | L* | a* | b* |
| 1 | 8.02 ± 0.09a | 0.56 ± 0.00a | 0.69 ± 0.00a | 353 ± 3a | 16.26 ± 1.34a | 11.19 ± 1.34a | 1.30 ± 0.03a | 1.38 ± 0.02a | 48.3 ± 0.2a | 2.4 ± 0.0a | 15.5 ± 0.0a |
| 2 | 7.40 ± 0.10b | 0.51 ± 0.00b | 0.70 ± 0.01a | 656 ± 35b | 32.26 ± 1.17b | 24.65 ± 2.49b | 1.77 ± 0.01b | 1.38 ± 0.03a | 40.8 ± 0.2b | 3.3 ± 0.0b | 15.8 ± 0.0b |
| 3 | 7.83 ± 0.07ab | 0.59 ± 0.00c | 0.78 ± 0.01b | 283 ± 9a | 21.55 ± 0.76c | 13.10.73a | 1.52 ± 0.02c | 1.29 ± 0.02b | 47.4 ± 0.3a | 3.0 ± 0.0c | 17.2 ± 0.1c |

*Note:* Means with different superscripts in each column are significantly different ($p < 0.05$).

of powder rehydration, which largely determines consumer preference. In particular, the ability of powders to form a solution or a suspension in water is acknowledged as the most reliable criterion to evaluate the behavior of powder in an aqueous solution (Tontul and Topuz 2017). The UK sample (variety 2) showed significantly higher dispersibility, solubility, and wetting time compared to the BR samples (variety 3) and the UK sample (variety 1). Data suggest that overall, the BR floured sample has a favorable rehydration profile, particularly if a short wetting time is desirable.

Water-holding capacity has a major impact on the sensory and textural properties of cereal-based products. These properties contribute to reduction in moisture depletion associated with texture, mouth feel, and flavor retention properties in food powders (Shevkani et al. 2014). Functional properties such as water- and oil-holding capacity also differed between varieties. Water-holding capacity was significantly higher for the UK saponin sample, followed by the BR sample, whereas oil-holding capacity was higher for the UK powdered samples (varieties 1 and 2). Color parameters indicated that the UK sample (variety 2) was darker, but no difference was detected between the BR sample (variety 3) and the UK sample (variety 1) in terms of lightness (L*). All three samples differed significantly in a* and b* parameters, indicating varietal differences in red and yellow color intensity.

## 4 | Discussion

### 4.1 | Nutrient Content

The protein content of fresh quinoa seed varieties analyzed was between 12.3% and 15.2%, which is higher than that of barley (10.8%), corn (10.2%), and rice (7.6%), and is comparable to wheat (14.3%) (Wright et al. 2002), and similar to other quinoa varieties (12%–18%) (Guo et al. 2025). The reference nutrient intake (RNI) for protein is set at 0.75 g of protein per kilogram bodyweight per day in adults. Therefore, if an adult weighs 74 kg, they will need $74 \times 0.75$ g/d = 55.5 g protein a day. A one hundred gram portion of fresh quinoa will deliver on average approximately a quarter (25%) of the required RNI. Although quinoa is a complete source of amino acids containing all nine essential ones, it has been shown that the first limiting amino acid for white quinoa varieties was Met + Cys (Manzanilla-Valdez et al. 2024). Not all plant-based protein sources are equally rich in essential amino acids, as cereals are usually deficient in Lys, while legumes are deficient in Met and Cys (De Bock et al. 2021, 2022). Quinoa gained popularity due to its balanced amino acid profile, being an excellent option to diversify the nutrient options in the human diet. Moreover, quinoa flour met the FAO/WHO requirements for infants, fulfilling the necessary requirements for essential amino acid content (WHO/FAO/UNU 2007; Mota et al. 2016). One hundred grams of each of the varieties analyzed in this study could deliver the RNI for His, Glu, and Thr, and between 33% and 72% of the rest of the essential amino acids. However, we cannot comment on tryptophan quantities of these varieties, as we did not perform this analysis. A recent study reported in vitro protein digestibility for several varieties of quinoas, all being > 76.9% in vitro; the protein digestibility-corrected amino acid



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score was the highest for yellow quinoa (34.92%) and the lowest for red quinoa (23.96%) (Manzanilla-Valdez et al. 2024). However, this study was performed on fresh seeds, and cooking quinoa seeds will increase these scores because it will reduce some of the anti-nutrients present.

The NSP content of the quinoa samples analyzed was largely of the insoluble type, being composed across varieties mainly of uronic acids (27% to 33% of NSP), glucose (34.5% to 36.6% of NSP), arabinose (18.6% to 25.8% of NSP), galactose (4.4% to 5.4% of NSP), xylose (3 and 3.95 of NSP), and mannose (1.6% to 2.6% of NSP). This composition indicates a diverse fiber composition with the presence of pectin, arabinoxylans, glucomannans, and hemicellulose. Estimating the fiber content using the calculation: dietary fiber = 1.33 × total NSP content, 100 g of quinoa varieties delivers between 19.25% and 25.78% of the daily recommendation for dietary fiber (30 g), based on the UK requirements (Public Health England 2015). Therefore, quinoa could easily contribute toward meeting and diversifying dietary fiber requirements. This is important, as only 6% to 8% of adults in the UK meet the daily recommendation for dietary fiber (Public Health England 2020), and underconsumption of fiber could lead to development of several chronic diseases (Fatima et al. 2023). Moreover, consumption of diverse types of fiber could contribute to beneficial health effects through increased gut microbial diversity (Calatayud et al. 2021; Ma et al. 2021).

All the quinoa varieties analyzed were rich sources of minerals. Analysis indicates that 100 g of fresh quinoa samples can contribute between 62% and 90% of Mg, 72%–104% of P, 21%–39% of K, 7%–18% of Ca, 54%–63% of Fe, and 30%–44% of Zn RNI intakes. Therefore, exploitation of quinoa as a source of nutrients could contribute toward tackling “hidden hunger,” which can occur without a deficit in energy intake because of consuming energy-dense, but nutrient-poor diets lacking in important nutrients such as iron, zinc, and vitamins (Lowe 2021). Furthermore, this presents opportunities for the food industry to incorporate quinoa flour as a sustainable source of ingredients in food formulations. However, it is important to properly assess quinoa's mineral bioavailability and to optimize methods to process the seed to manufacture food products to maximize the reduction of antinutrients such as saponins, phytic acid, trypsin inhibitors, and oxalates found in quinoa to maximize the absorption of minerals (Manzanilla-Valdez et al. 2024).

### 4.2 | Phytochemical Content

A comprehensive phytochemical analysis consisting of quantification of a total of 158 molecules was performed on the quinoa samples using a targeted LC–MS/MS method. This study also determined the phytochemicals within the seed, respectively, molecules extracted in free and bound forms (following acid or alkaline hydrolysis). Indole 3-pyruvic acid was the most abundant molecule quantified in all the quinoa samples. This could be produced following microbial metabolism of tryptophan, and potentially indicating degradation of protein, specifically oxidation of tryptophan, being found in the highest amount in variety 2 grown in the UK, mainly in free form. Once we subtracted the values for indole 3-pyruvic acid, varieties 1 and 2 had similar amounts of total phytochemicals measured (resulted by summing individual phytochemicals measured by LC–MS): 298 mg and 306 mg/kg, respectively (variety 3 had 263 mg/kg). Furthermore, all three varieties were more abundant in molecules extracted in bound form (alkali- and acid-labile), with variety 1 having over 88% of the molecules in bound form, variety 2 having 67% of the molecules in bound form, and variety 3 having 62% of the molecules in bound form. This indicates that once consumed, quinoa seeds can deliver these molecules in the gastrointestinal tract (GIT) at a later time, potentially being released in the colon and metabolized by the gut microbiota. Ferulic and vanillic acids were the most abundant phenolic acids in all varieties, mainly extracted following hydrolysis, indicating that they are found in bound form in the seed, and therefore released in the colon following quinoa consumption. Research carried out into microbial fermentation of ferulic acid has revealed that ferulic acid metabolites play a role in enhancing gut health as recently reviewed (Chen et al. 2024), highlighting their importance not only in direct dietary consumption but also in prebiotic formulations designed to support the microbiome. Vanillic acid has also been studied as a potential component in nutritional therapies for ulcerative colitis (Zhao et al. 2025), emphasizing its role in regulating the gut microbiota and inflammatory pathways, which may have significant nutritional relevance in managing inflammatory bowel diseases.

Quercetin and kaempferol were also found to be abundant in all the quinoa samples and found mainly in bound form, being released after acid hydrolysis. Both quercetin and kaempferol have properties that favorably modulate the gut microbiota, enhance intestinal barrier function, and exert anti-inflammatory effects, collectively supporting overall gut health. Research indicates that quercetin intake can alter the composition of gut microbiota, enhancing diversity and promoting beneficial bacteria such as Bacteroides, Bifidobacterium, Lactobacillus, and Clostridia. This modulation helps rebalance the gut microbiota, potentially alleviating conditions like colitis (Lyu et al. 2022). Quercetin has the potential for use in the treatment of colitis by maintaining the mucosal barrier, modulating inflammation, and reducing oxidation stress, which may depend on the reversal of gut microbiota dysbiosis (Lv et al. 2024). Supplementation with kaempferol has been linked to changes in the gut microbiota composition, including increased populations of beneficial bacteria and decreased levels of potentially harmful microbes. This modulation supports intestinal health and may contribute to the anti-inflammatory effects observed in animal models (Bian et al. 2022). Overall, quinoa consumption could not only diversify the dietary nutrients but also could contribute non-nutrient components that could further benefit human health.

Previous research has identified several health benefits associated with quinoa consumption. Specifically, in terms of blood sugar regulation, a study involving 210 patients with type 2 diabetes demonstrated that incorporating two slices of quinoa bread into daily diets for 6 months significantly reduced fasting plasma glucose concentrations (Li et al. 2018). Quinoa consumption could lead to improved lipid profiles, including reduced triglyceride levels, enhancing cardiovascular health (Simnadis et al. 2015); also, quinoa could be used in weight management, leading to decreased weight gain and improved lipid profiles.



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## 4.3 | Physical Properties

The observed differences in physical properties between the samples are largely attributed to the differences in the proximate compositions of the UK and BR varieties (Table 6). Reconstitution properties are determined primarily by the surface composition and hydrophobicity of the samples (Fitzpatrick et al. 2016). The poor reconstitution properties of the UK flour (variety 1) are mainly attributed to the significantly higher fat content (6.19%) compared to the BR sample (3.48%). Furthermore, solubility is related to the hydrophilic–hydrophobic balance of the proteins and the thermodynamics of protein–solvent interactions (Abugoch James 2009). The significantly higher protein content of the BR sample may also account for the increased solubility of the former compared to the UK flour (variety 1). The increased solubility and dispersibility of the UK sample (variety 2) may also be attributed to the presence of glycosides. Saponin content in quinoa can vary from 0.14% to 2.3% (Fenwick et al. 1991), and in some varieties, it can be as high as 7.5% of the total composition of the whole quinoa flour (Gómez-Caravaca et al. 2011). Saponins, due to their amphiphilic nature, are surface-active molecules with the documented ability to enhance solubility, mediated by a micellar solubilization mechanism (Güçlü-Üstündağ and Mazza 2007).

The UK (variety 2) and BR (variety 3) samples showed a significantly higher water-holding capacity in relation to the other UK sample (variety 1). BR samples contain higher levels of hydrophilic macromolecules, such as protein and soluble fiber (NSP), which can bind to water and contribute to the high water-holding capacity (Tudorache et al. 2020). Data indicate that the soluble fraction of the saponin compounds contributes significantly to this property demonstrated by the UK saponin sample. On the other hand, oil-holding capacity was higher for the UK cultivar samples. This property correlates with the presence of hydrophobic, non-polar amino acid side chains on the protein molecule surface (Falade et al. 2014).

Loose and bulk density values of the BR sample were significantly higher than those of the UK samples (varieties 1 and 2). Previous work ascribed this effect to increased total solid content and moisture levels (Neacsu et al. 2022). However, in this study, UK and BR flours showed similar dry matter and moisture levels. The size, shape, and surface properties of the seed particles can affect bulk density; however, further work is needed to verify this hypothesis for the samples of the present study (Bicudo et al. 2015).

Both UK and BR samples showed similar white–beige color, as indicated by the relatively high recorded mean of the lightness (L*) parameter. Previous work has reported even higher luminosity and similar values for redness (a*) and yellowness (b*) parameters for quinoa seeds produced in Brazil (Sampaio et al. 2020). Color variations in quinoa ranging from beige to gold have been reported, as also pink or red quinoa (Vega-Gálvez et al. 2010). White color is a desirable attribute for food powders used as additives in food formulations because they have a minor impact on the final color of the product and thus they do not influence drastically consumer's opinion (Romano et al. 2020).

## 5 | Conclusions

Quinoa samples were found to be a complete source of protein, providing all the essential amino acids, and also rich in insoluble fiber and minerals, including magnesium, iron, potassium, and zinc. Quinoa samples were also found to be rich in bioactive phytochemicals such as ferulic acid, vanillic acid, quercetin, and kaempferol, mainly in bound form, being released after hydrolysis, and therefore with the potential to be metabolized at the colon level and improve gut health.

The physical properties of the BR sample showed desirable handling and reconstitution properties, suggesting that the specific cultivar could be beneficial for long storage and transport of the powder, in addition to food formulations that require rapid and adequate rehydration.

These findings on the nutrient composition, physical properties, and phytochemical content of quinoa samples are encouraging, as they indicate that this crop could be used to meet and diversify human dietary requirements, while also potentially spurring the food industry to develop novel and healthier food formulations, which support agricultural diversity. Quinoa could represent a beneficial addition to the diets of individuals with various dietary needs and health goals.

### Author Contributions

Conceptualization: Madalina Neacsu, Vassilios Raikos, and Wendy R. Russell. Methodology: Madalina Neacsu, Vassilios Raikos, Wendy R. Russell, and Shirley De Lima Sampaio. Formal analysis: Shirley De Lima Sampaio, Nicholas J. Vaughan, Vassilios Raikos, Helen E. Hayes, Donna Henderson, and Gary J. Duncan. Data curation: Madalina Neacsu, Shirley De Lima Sampaio, Helen E. Hayes, Vassilios Raikos, and Gary J. Duncan. Writing – original draft preparation: Madalina Neacsu and Vassilios Raikos. Writing – review and editing: Madalina Neacsu, Vassilios Raikos, and Wendy R. Russell. Visualization: Madalina Neacsu, Vassilios Raikos, and Wendy R. Russell. Supervision: Madalina Neacsu, Vassilios Raikos, and Wendy R. Russell. All authors have read and agreed to the published version of the manuscript.

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### Conflicts of Interest

The authors declare no conflicts of interest.

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