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Impact of cooking methods on the techno-functionality and *in vitro* digestibility of underutilized climate-resilient pulses.

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Abstract

Underutilized pulses are promising sustainable ingredients for plant-based foods; however, comprehensive information on the effects of thermal processing on their nutritional and functional quality remains limited. This study evaluated the effects of conventional boiling and pressure cooking on the nutritional composition, physicochemical and techno-functional properties, mineral bioaccessibility, antioxidant related parameters, and starch digestibility of *Vigna unguiculata* and *Lablab purpureus* flours. Protein (23.66–28.80 g/100 g dw), total dietary fiber (24.09–29.30 g/100 g dw), and total starch (38.97–46.82 g/100 g dw) remained nutritionally relevant across treatments, although several composition variables showed species- and treatment-dependent responses. The

flours exhibited high water- and oil-holding capacities (4.6–6.3 and 2.8–3.2 g/g, respectively). Mineral concentrations on a dry-weight basis differed among processing conditions; because cooking yield and mineral mass balance were not determined, these differences were not interpreted as true retention. After *in vitro* digestion, boiling was associated with higher bioaccessibility of Ca, Mg, Zn, and P under the conditions evaluated; for example, Zn bioaccessibility ranged from 5.88 to 14.58% and P bioaccessibility from 8.51 to 13.00%. Antioxidant responses were species- and assay-dependent, and neither cooking condition was consistently favorable across TPC, ABTS, FRAP, and DPPH. All cooked samples showed relatively low predicted glycemic index values (49.68–50.87). Overall, the results demonstrate that the effects of thermal processing depend on the pulse, the analytical endpoint, and the complete processing condition, supporting the potential of *V. unguiculata* and the underutilized *L. purpureus* as ingredients for nutritious plant-based foods.

Keywords: Fabaceae, Pulses, Legumes, Functional ingredients; Mineral profile; plant based-foods, glycemic index

1. Introduction

Over the past decades, the increasing demand for healthy and sustainable foods has driven a shift toward dietary patterns with a greater contribution of plant-based proteins (Anyiam et al., 2025). This transition is motivated not only by the need to reduce the environmental impact associated with food production but also by the growing recognition of the role of plant-based foods in the prevention of chronic diseases and the development of more sustainable food systems. In this context, pulses have gained increasing attention due to their high nutritional value and their ability to fix atmospheric nitrogen through symbiotic associations with soil bacteria, thereby reducing the need for synthetic nitrogen fertilizers and contributing to the maintenance of soil fertility (Conti et al., 2021; Gorbe et al., 2026; X. Zhang et al., 2024).

Pulse seeds are an important source of protein (17–30% dw) and provide a favorable amino acid profile, together with complex carbohydrates, dietary fiber, vitamins, minerals, and a wide range of bioactive compounds, while containing relatively low amounts of fat compared with other plant-based protein sources (Affrifah et al., 2023; J. Boye et al., 2010; X. Zhang et al., 2024). This unique nutritional composition has been associated with a reduced risk of cardiovascular disease, type 2 diabetes, obesity, and other metabolic disorders, making pulses a key component of healthy dietary patterns (J. Boye et al., 2010; Conti et al., 2021). At the same time, the food industry has shown growing interest in pulses as raw materials for the development of plant-based beverages, meat analogues, extruded products, fortified flours, and gluten-free foods suitable for celiacs, in which the functional properties of their proteins and polysaccharides largely determine the technological performance of the resulting ingredients (Anyiam et al., 2025; Devkota et al., 2025; M. Li et al., 2023).

Despite the substantial expansion of research on pulses in recent years, most studies have focused on major commercial species, such as common bean (*Phaseolus vulgaris*), lentil (*Lens culinaris*), chickpea (*Cicer arietinum*), pea (*Pisum sativum*), and soybean (*Glycine max)*. In contrast, many pulses traditionally cultivated in tropical regions remain underexplored despite their considerable nutritional, agronomic, and technological potential (Samal et al., 2023). Among these are cowpea (*Vigna unguiculata*) and hyacinth bean (*Lablab purpureus*), two species well adapted to drought conditions, high temperatures, and low-fertility soils, making them promising alternatives for diversifying plant protein sources in the face of climate change–related challenges (Padhi et al., 2022; Shubha et al., 2023).

Vigna unguiculata is one of the most important grain pulses cultivated in arid, semi-arid, and subtropical regions owing to its short growing cycle, high drought tolerance, and ability to maintain satisfactory yields under conditions of limited water availability (Hall, 2012). Several studies have reported that its seeds are rich in proteins, complex carbohydrates, dietary fiber, iron, zinc, and other essential minerals, as well as phenolic compounds with antioxidant activity (Antova et al., 2014; Padhi et al., 2022). Likewise, *Lablab purpureus* is characterized by a high protein content and a nutritional composition comparable to that of other widely consumed pulses, which has stimulated growing interest in its use for functional foods and plant-based formulations (Hossain et al., 2016; Krishnan et al., 2025). Despite these advantages, both species are still considered underutilized pulses because of the limited information available on their nutritional and functional characteristics, particularly regarding the effects of processing on nutrient availability, functional properties, and their potential application as food ingredients. This knowledge gap hinders the valorization of these species and limits their utilization in the development of novel plant-based foods (J. Boye et al., 2010; Samal et al., 2023).

Like other pulses, the seeds of *Vigna unguiculata* and *Lablab purpureus* contain several antinutritional compounds, including phytates, tannins, protease inhibitors, and lectins, as well as a cellular structure that limits the accessibility of stored nutrients to digestive enzymes within the cotyledons (Conti et al., 2021). Therefore, thermal processing is an essential step prior to consumption, as it improves food safety, reduces the content of antinutritional factors, and enhances nutrient bioavailability and bioaccessibility (Abbas & Ahmad, 2018; Haji et al., 2024; Parada & Aguilera, 2007a). Among household preparation methods, boiling and pressure cooking are the most commonly used, both inducing structural changes such as starch gelatinization, protein denaturation, cell wall softening, and the partial solubilization of polysaccharides and phenolic compounds, thereby modifying the chemical composition, texture, and nutritional quality of the seeds (Carboni et al., 2024; Haji et al., 2024; Osuna-Gallardo et al., 2023). Although these transformations improve several aspects of nutritional quality, they may also result in losses of water-soluble vitamins, phenolic compounds, and certain minerals through leaching into the cooking water (Abbas & Ahmad, 2018; Raes et al., 2014).

Differences between conventional boiling and pressure cooking were expected because these methods involve distinct combinations of temperature, pressure, cooking time, and water-to-seed ratio. Pressure cooking, which applies higher temperatures and pressure for a shorter period, was expected to induce more extensive thermal modifications and potentially increase starch susceptibility to enzymatic hydrolysis, whereas its shorter cooking time and lower water requirement could reduce the leaching of soluble components. In contrast, conventional boiling involves longer exposure to water and was therefore expected to favor greater losses of water-soluble constituents into the cooking medium (Deol & Bains, 2010; Eyaru et al., 2009). Consequently, the two cooking

methods were expected to have different effects on the nutritional, digestive, and techno-functional properties of the pulses.

Beyond their nutritional implications, thermal processing also plays a key role in determining the technological functionality of pulses. Protein denaturation, starch gelatinization, and modifications of the food matrix alter key physicochemical and techno-functional properties, including water and oil absorption capacity, swelling power, solubility, and emulsifying and foaming properties (J. Boye et al., 2010; Duque-Estrada et al., 2026). These properties are critical to the performance of pulses as food ingredients because they influence the stability, texture, and consumer acceptability of products such as plant-based beverages, meat analogues, baked goods, and extruded foods (Carboni et al., 2024; X. Zhang et al., 2024).

In recent years, pulse research has increasingly focused on understanding how processing modifies the structure and functionality of their components, as well as its impact on macronutrient digestibility, mineral bioaccessibility, and techno-functional properties, all of which determine their nutritional value and potential application as food ingredients (Devkota et al., 2025; Duque-Estrada et al., 2026; M. Li et al., 2023). Nevertheless, information on these aspects remains limited for *Vigna unguiculata* and *Lablab purpureus*, particularly regarding the effects of thermal processing. Therefore, the aim of the present study was to evaluate the influence of two thermal processing methods on the nutritional quality, physicochemical and techno-functional properties, mineral bioaccessibility, and starch digestibility of *Vigna unguiculata* and *Lablab purpureus* seeds, thereby providing evidence to support their potential use as ingredients for the development of plant-based foods.

2. Materials and Methods

2.1 Raw Material

Two locally consumed pulses from Loja province, Ecuador, were selected for the study: cowpea (*Vigna unguiculata*), locally known as firigüero, and hyacinth bean (*Lablab purpureus*), locally known as zarandaja. Dry grains were obtained from Loja province, Ecuador, vacuum-packed in plastic bags, and stored until analysis.

2.2 Cooking Conditions

Preliminary cooking trials were conducted for each pulse and cooking method to identify three cooking times encompassing the expected optimum cooking time. These cooking times were subsequently evaluated by sensory analysis using a panel of eight assessors in accordance with the general principles described in ISO 13299 (ISO, 2016). All methods were performed in accordance with the relevant guidelines and regulations, following ethical approval by the Committee of Ethics and Integral Research at Miguel Hernández University (code: PRL.RTA.RLG.MJCC.26) and written informed consent from all participants. Samples were identified with random three-digit codes and presented in random order. Assessors evaluated hardness by simultaneously chewing at least three grains from each sample to minimize variability among individual grains. The samples were first ranked from the softest to the hardest and subsequently scored for hardness using a 5-point unstructured line scale anchored at 0 ("very soft") and 5 ("very hard"). Hardness scores were analyzed by one-way analysis of variance (ANOVA), followed by Tukey's honestly significant difference test (HSD) at a significance level of $p < 0.05$ using the statistical software SPSS 19.0 (SPSS Inc., Chicago, IL). The optimum cooking time for each pulse and cooking method was defined as the shortest cooking time whose hardness score did not differ significantly from that of the subsequent longer cooking time. Prior to cooking, the pulses were soaked for 5 h in potable water at a 1:2 w/v ratio (Q. Li et al., 2016) at room temperature. After soaking, the water was discarded, and the pulses were then cooked by conventional boiling or pressure cooking under the conditions

summarized in Table 1. Different seed-to-water ratios were used for conventional boiling and pressure cooking because pressure cooking was carried out in a closed system, minimizing evaporative water losses and allowing complete grain hydration with a lower water volume (Khattab & Arntfield, 2009). All cooking treatments were performed in triplicate. After cooking, the samples were ground using an electric food processor (Kitchen Aid) at low speed for 30 s. The samples were then freeze-dried (Labconco Free Zone 12) at –50 °C and 15 Pa. The freeze-dried samples were milled and homogenized prior to subsequent analyses. Particle-size characterization showed that 97.09% of the flour particles were smaller than 500 µm. Finally, the samples were stored in laminated bags with airtight closures and kept at 2 °C in darkness (Q. Li et al., 2016). In total six samples were studied, which were codified as raw cowpea (C-R); boiled cowpea (C-B), pressure-cooked cowpea (C-P), raw hyacinth bean (HB-R), boiled hyacinth bean (HB-B) and pressure-cooked hyacinth bean (HB-P).

2.3 Chemical Composition

2.3.1 Proximate Composition Analysis

Moisture, ash, lipid, and protein contents were determined according to AOAC Official methods 925.10, 923.03, 922.06, and 960.52, respectively (Horwitz & Latimer, 2007). Moisture was expressed as g/100 g sample, whereas the remaining composition variables were expressed on a dry-weight basis. Total dietary fiber (TDF) was measured using an enzymatic-gravimetric method based on AOAC Official Method No. 985.29. Resistant (RS) and non-resistant starch (NRS) contents were quantified using the AOAC 2002.02 enzymatic method with the K-RSTAR kit (Megazyme). Briefly, starch was hydrolyzed and solubilized by pancreatic α-amylase, followed by incubation at 37 °C for 16 h under horizontal agitation at 60 rpm, ethanol extraction, centrifugation (Thermo Scientific Sorvall ST8) at 1207 x g for 10 min, and recovery of supernatants. The resulting

sediment was used for resistant starch (RS) determination by treatment with KOH in an ice bath at 700 rpm for 20 min, neutralization with acetate buffer, enzymatic digestion with amyloglucosidase (3300 U/mL), incubation at 50 °C for 30 min, centrifugation at 1207 x g for 10 min, and glucose quantification using GOPOD reagent (glucose oxidase–peroxidase) at 510 nm (DR 6000 spectrophotometer, HACH). Values were converted to anhydroglucose equivalents using a correction factor (162/180) and expressed as g/100 g of sample (dry basis). The supernatant was collected in a 50 mL volumetric flask and adjusted to volume with acetate buffer. An aliquot was then treated with amyloglucosidase and GOPOD reagent, incubated at 50 °C for 20 min, and absorbance was measured at 510 nm; NRS was calculated as described for RS. Total starch content was obtained as the sum of resistant and non-resistant starch.

2.3.2 Mineral profile determination

For both raw and cooked samples, the analysis began with ash obtained by calcination at 600°C. The resulting ash was solubilized with 40 mL of HCl (1:3, v/v) and a few drops of concentrated HNO_3. The mixture was carefully heated to boiling, cooled to room temperature and subsequently diluted with distilled water to a defined final volume. Magnesium, calcium, iron, copper, and zinc were quantified using the AOAC 999.10 method by atomic absorption spectroscopy (Perkin Elmer Analyst 400). Phosphorus was quantified using the AOAC 986.24 method by UV–visible spectroscopy (BioSmartest model 5600) at 400 nm, which is based on the formation of a molybdovanadate complex measured at 400 nm. Calibration curves were prepared using standards, and mineral content was expressed as mg/100 g of sample on a dry weight basis.

2.4 Physicochemical Properties

Bulk density was expressed as the weight of the sample (g) per unit volume of powder (g/mL). A 5% (w/v) aqueous solution of the samples was used to determine pH using a

pH meter (Mettler Toledo), and titratable acidity (TA) was determined by titrating an aqueous suspension of the sample with 0.1 N NaOH and expressed as % citric acid.

2.5 Techno-functional Properties

The functional properties of the samples were determined following established methodologies with slight modifications. Water holding capacity (WHC) was measured by dispersing 1 g of sample in 30 mL of distilled water, allowing the mixture to stand for 24 h, and centrifuging at 1207 x g for 20 min; the residue was then dried at 102 °C for 12 h, and results were expressed as g of water retained per g of sample (Robertson et al., 2000). Oil holding capacity (OHC) was measured, by mixing 1 g of sample with 10 mL of vegetable oil, shaking for 1 min, allowing the mixture to stand for 30 min at 20 °C, and centrifuging at 1207 x g for 20 min; results were expressed as g of oil retained per g of sample (Chau & Huang, 2003). Emulsifying capacity (EC) was determined by homogenizing 1 g of sample with 20 mL of distilled water for 10 s, followed by the addition of 7 mL of vegetable oil; after centrifugation at 1207 x g for 1 h, the emulsified layer was measured and expressed as a percentage of the total volume (Chau & Huang, 2003). Emulsion stability (ES) was assessed using a similar procedure, incorporating a heating step at 80 °C for 30 min prior to centrifugation at 162 x g for 5 min, and results were expressed as the percentage of the emulsified layer relative to the total volume (Tamangwa et al., 2023). Foaming capacity (FC) was determined by homogenizing (HAMILTON BEACH H-4260A mixer) 1 g of sample with 50 mL of distilled water for 5 min, recording foam volume immediately and after 30 s, and expressing results as a percentage increase in volume (Bencini, 1986), while foam stability (FS) was evaluated under the same conditions by recording foam volume immediately after foam formation (t = 0) and after 5, 10, 15, 30, 60, and 120 min. The initial foam volume at t = 0 was used as the reference value to calculate foam stability at each subsequent time point. Finally, gelling capacity (GC)

was evaluated based on the procedure reported by J. I. Boye et al. (2010) with slight modifications. Sample dispersions (4, 8, and 12%, w/v) were prepared in distilled water in test tubes and heated in a boiling water bath (100 °C). To monitor gel formation, independent tubes were evaluated every 15 min during the 60 min heating period and immediately subjected to the tube inversion test. A firm gel was considered to have formed when the sample remained stationary upon tube inversion. The minimum heating time required for gel formation at each concentration was recorded as the gelation time. After heating, the gels were cooled under running tap water and subsequently stored at −18 °C for 1 h to confirm gel stability.

2.6 Total phenolic content and Antioxidant Capacity

Pulse extracts were obtained following the methodology described Pérez-Jiménez & Saura-Calixto (2006). Briefly, 3 g of sample were weighed and mixed with 20 mL of a methanol/water solution (50:50, v/v, pH 2). The mixture was shaken at 180 rpm for 1 h and subsequently centrifuged at 1090 x g for 10 min. The supernatant was collected, and the residue was re-extracted with 20 mL of an acetone/water solution (70:30, v/v), followed by shaking under the same conditions and centrifugation at 1207 x g for 10 min. Both supernatants were combined and used for further analysis. Total phenolic content (TPC) was determined by Folin–Ciocalteu assay, with slight modifications. Briefly, 240 µL of distilled water, 15 µL of sample extract, and 15 µL of Folin–Ciocalteu reagent was mixed in a 96-well microplate and allowed to react for 15 min. Then, 30 µL of 20% (w/v) sodium carbonate solution were added, and the mixture was incubated for an additional 5 min. Absorbance was measured at 725 nm using a BioTek Epoch 2 microplate reader. TPC was calculated based on the calibration curve of gallic acid, and results were expressed as mg of gallic acid equivalents (GAE) / 100 g of sample on a dry weight basis. The antioxidant capacity of the extracts was evaluated using the 2,2-diphenyl-1-

picrylhydrazyl (DPPH) radical scavenging assay, the 2,2′-azinobis-(3-ethylbenzothiazoline-6-sulfonic acid) (ABTS) assay, and the ferric reducing antioxidant power (FRAP) assay, following the procedure described by Thaipong et al. (2006), with slight modifications. Results were expressed as µmol Trolox equivalents (TE) / g dry weight (dw).

2.7 *In Vitro* Gastrointestinal Digestion

In vitro gastrointestinal digestion was performed using the static INFOGEST protocol (Minekus et al., 2014; Brodkorb et al., 2019), with oral, gastric, and intestinal phases at 37°C under orbital agitation (Orbital Shaker NB-101 M). For the oral phase, 5 g of cooked pulse sample were mixed with 3.5 mL simulated salivary fluid (SSF), 0.5 mL salivary α-amylase stock solution (1500 U/mL), 25 µL $CaCl_2$ (0.3 M), and 975 µL distilled water, followed by incubation at 37 °C and 170 rpm for 2 min. For the gastric phase, 7.5 mL simulated gastric fluid (SGF), 2 mL porcine pepsin stock solution (25,000 U/mL), 5 µL $CaCl_2$ (0.3 M), 0.2 mL HCl (1 M) to adjust the pH to 3.0, and 0.295 mL distilled water were added, followed by incubation at 37 °C and 170 rpm for 2 h. For the intestinal phase, 11 mL simulated intestinal fluid (SIF), 5 mL pancreatin stock solution (800 U/mL), 40 µL $CaCl_2$ (0.3 M), 0.15 mL NaOH (1 M) to adjust the pH to 7.0, and 3.81 mL distilled water were added, and samples were incubated at 37 °C and 170 rpm for 2 h. Enzyme activities reported above correspond to the stock solutions used in the assay. Enzyme inactivation was carried out by thermal shock.

2.7.1 Starch Digestion Kinetics and Estimation of Glycemic Index

Starch digestion kinetics were assessed according to the method described by Díaz-Osorio et al. (2019) and Lucas-González et al. (2021), with slight modifications. During the intestinal phase of *in vitro* digestion, 0.1 mL aliquots of the supernatant were collected at 0, 30, 60, 90, 120, 180, and 200 min and transferred into 50 mL volumetric flasks. Enzymatic activity was halted by rapid cooling in an ice bath for 20 min, and samples

were subsequently stored at 4 °C until analysis. Non-resistant starch content was later quantified in all samples (see Section 2.3.1). The kinetic parameter, specifically the kinetic constant (*k*), was calculated following the linearized first-order kinetic equation (Equation 1), plotting (t; min) (y) versus ln ($C\infty$ - C_t). Although the *in vitro* digestion assay was conducted up to 200 min, the kinetic parameters were calculated using data up to 120 min. This time point was selected because it corresponds to the onset of the hydrolysis plateau, as previously reported for similar starch-based systems (Collar & Armero, 2018). The area under the curve (AUC) was calculated using the trapezoidal rule from plots of non-resistant starch content (C_1, C_2, …) versus time (t_1, t_2, …), using the equation (2).

$$C = C(\infty)(1 - e^{(-kt)} \quad (1)$$

$$AUC = \sum_{i=1}^{n-1} \left[\frac{C_i + C_{i+1}}{2} \times (t_{i+1} - t_i) \right] \quad (2)$$

The hydrolysis index (HI) was calculated as the ratio between the AUC of each cooked sample with that of a white bread (reference food), which was digested in the same conditions of the samples (Goñi et al., 1997). Finally, the predicted glycemic index was obtained using the equation (3).

$$pGI = 39.71 + 0.549\ HI \quad (3)$$

2.7.2 Mineral Bioaccessibility

The bioaccessible fraction of each mineral was calculated as the ratio between the mineral content in the digested sample and the total content in the undigested sample, expressed as a percentage, as commonly described in previous studies (Kumari & Platel, 2017). In brief, after the intestinal *in vitro* digestion phase, samples were centrifuged at 3000 x g for 15 min (Charette et al., 2021), and the resulting supernatant was collected for mineral analysis following the methodology described in Section 2.3.2.

2.8 Statistical analysis

Statistical analyses were carried out using PAST software version 5.2. For variables measured in raw and cooked flours, two-way ANOVA was applied with pulse species and processing treatment as fixed factors, including their interaction. For digestion-related variables evaluated only in cooked samples, two-way ANOVA included pulse species, cooking treatment, and their interaction. Three independent cooking batches were considered the experimental replicates (n = 3). When technical determinations were performed, they were averaged within each batch before inferential analysis. Results are expressed as mean ± standard deviation (SD) of the three independent batches. When significant effects were detected, means were compared using Tukey's HSD test at $p < 0.05$. Values reported as $p = 0.000$ by the software are presented as $p < 0.001$.

Foam stability was analyzed using a mixed-effects model including pulse species, cooking treatment, time (5, 10, 15, 30, 60, and 120 min), and their interactions as fixed effects, with experimental batch (ID) included as a random effect to account for repeated measurements over time. The t = 0 measurement was used only as the reference for calculating percentage foam stability and was not included in the inferential model. Gelation time was analyzed by three-way ANOVA with pulse species, cooking treatment, and flour concentration (4, 8, and 12%, w/v) as fixed factors, including all interactions. Significant effects were followed by Tukey's HSD test at $p < 0.05$.

Two Principal Component Analysis (PCA) were conducted as multivariate statistical methods to reduce data dimensionality and explore the relationships among: (1) chemical, mineral, physicochemical, and technofunctional variables; and (2) hydrolysis parameters (kinetic constant, estimated glycemic index, hydrolysis index, and starch hydrolysis) and mineral bioaccessibility across the different pulse flours. A biplot representation was generated to simultaneously visualize the spatial distribution of the samples and the

contribution of the original variables to each principal component. Prior to performing PCAs, data were normalized using Z-score. Biplots representations were performed and generated using R software.

3. Results and Discussion

3.1 Chemical composition

Raw cowpea and hyacinth bean flours exhibited broadly similar proximate profiles for moisture, protein, total dietary fiber (TDF), and ash content (Table 2). The primary nutritional differences between raw seeds were significantly higher fat and total starch contents in C-R, alongside a higher initial resistant starch (RS) fraction in HB-R ($p < 0.05$). Non-resistant starch constituted the predominant carbohydrate fraction in both species. Overall, both species displayed a nutritional profile typical of edible pulses, characterized by high complex carbohydrate content, moderate protein, and very low-fat levels (Arroqui et al., 2025; Hossain et al., 2016). Their protein contents fell within ranges reported for commercial crops such as pea (*Pisum sativum*) (14–34 g/100 g dw*)*, lentil (*Lens culinaris*) (23–31 g/100 g dw) and chickpea (*Cicer arietinum*) (18–29 g/100 g dw), whereas soybean (*Glycine max*) exhibits a distinctly higher protein and lipid profile alongside lower starch levels (J. Boye et al., 2010; W. Zhang et al., 2024). Substantial TDF contents were observed in both C-R and HB-R, reinforcing their potential as novel fiber-rich ingredients (Amoah et al., 2023).

Thermal processing did not significantly alter overall protein, TDF, or total starch concentrations ($p > 0.05$), meaning any minor numerical variations following cooking should not be interpreted as treatment-induced changes. However, processing selectively affected specific fiber and starch sub-fractions: insoluble dietary fiber (IDF) significantly decreased in HB-P ($p < 0.05$), and RS levels significantly dropped after both boiling (HB-B) and pressure cooking (HB-P) ($p < 0.05$). Initial RS values in raw hyacinth bean (HB-

R) aligned with higher literature ranges reported for pulses (3–7 g/100 g dw) (Carboni et al., 2024). The observed decrease in RS following thermal processing is likely attributable to thermal gelatinization, which is known to disrupt native RS2 crystalline structure and enhance susceptibility to enzymatic cleavage (Arroqui et al., 2025; Inan Eroglu & Buyuktuncer, 2017). Although heating and subsequent cooling cycles can theoretically promote retrograded RS3 formation (Noraidah et al., 2023; Sharma & Yadav, 2010), the net reduction observed here suggests that starch gelatinization predominated over retrogradation under the applied processing conditions.

Regarding ash content, boiling significantly lowered ash concentrations relative to raw and pressure-cooked flours ($p<0.05$). This reduction consists of convective leaching and diffusion of water-soluble mineral constituents into the cooking liquor, a phenomenon widely reported during aqueous thermal processing of pulses (Khatoon & Prakash, 2004; Shimelis & Rakshit, 2005). Because cooking yield, total cooked mass, and mineral concentrations in the discharge water were not quantified, these concentration values cannot be extrapolated to absolute mineral retention or true loss. Nevertheless, existing literature suggests that shorter cooking durations or reduced water-to-seed ratios effectively mitigate mineral leaching into aqueous media (Khatoon & Prakash, 2006).

3.2 Mineral profile

Potassium (K), magnesium (Mg), phosphorus (P), and calcium (Ca) were the predominant minerals across both raw pulse flours (Table 3). Overall, thermal processing significantly altered mineral concentrations ($p < 0.001$), with the direction and magnitude of these shifts governed by processing mode and mineral species. In raw flours, baseline concentrations reflected typical pulse profiles; cowpea exhibited higher initial K, Cu, and Zn levels, whereas hyacinth bean was richer in Fe and Ca ($p < 0.05$). Notably, a 100 g

portion of raw flour from either species fulfills over 15% of the Nutrient Reference Values (NRVs) for Mg, K, Fe, Cu, and Zn, meeting the criteria for "source of" mineral claims under Regulation (EC) No 1924/2006. Thermal treatments—particularly conventional boiling—consistently led to reduced dry-weight concentrations for most minerals (e.g., P, K, Mg, Ca, and Cu). Boiled samples exhibited the lowest values for Ca (65.52–66.30 mg/100 g dw) and Cu (0.34 mg/100 g dw in cowpea). This pattern aligns with convective leaching and cell-wall disruption, which facilitate the diffusion of water-soluble mineral ions into the cooking medium (Abbas & Ahmad, 2018; Kouakou et al., 2019; Y. Xu et al., 2016). Pressure cooking generally preserved higher mineral concentrations than boiling. This retention effect likely reflects the combined influence of shorter thermal exposure, reduced water volume, and a closed system, which limits mass transfer into the liquid phase (Carvalho et al., 2012). Micromineral dynamics exhibited marked species-dependent responses to processing ($p < 0.05$) for species x treatment interaction). Raw hyacinth bean contained the highest Fe concentration (3.67 mg/100 g dw), which decreased following both thermal treatments. Conversely, Zn displayed divergent species trends: while thermal processing reduced Zn concentration in cowpea (from 16.77 to 8.69–9.66 mg/100 g dw), hyacinth bean showed higher dry-weight Zn levels after pressure cooking (13.82 mg/100 g dw) compared to its raw state (8.09 mg/100 g dw). Because total Zn was determined via complete acid digestion, matrix-release mechanisms alone cannot account for this relative increase. Because cooking yields, post-processing mass, and liquid-phase mineral leaching were not directly quantified, these observations reflect relative

concentration shifts on a dry-weight basis—driven by dry-matter redistribution and matrix reorganization—rather than absolute mass gains or losses (Hummel et al., 2020). The loss of soluble compounds in hyacinth beans could have influenced the Zn concentrations. Furthermore, these total element concentrations do not account for mineral speciation or the influence of antinutritional complexes (e.g., phytates), which ultimately govern downstream bioaccessibility.

3.3 Physicochemical properties

The thermal treatments applied to the pulses produced significant changes in their physicochemical properties. As shown in Supplementary Table 1, pH increased while titratable acidity decreased ($p < 0.05$). During soaking and cooking, soluble compounds such as organic acids may leach into the soaking/cooking water, resulting in reduced titratable acidity and a shift of pH toward more alkaline values. Osuna-Gallardo et al. (2023) reported that pH determination in pulse flours is important because it affects their functional properties, particularly those related to proteins. Similar behavior has been reported in several pulses such as chickpea, lentil, and bean, where pH significantly increased after treatments including soaking, cooking, and dehydration (Aguilera, 2009; Sarmento, 2012).

Regarding density, both pulses showed a significant reduction after cooking (Table S1). This result is associated with the structural changes occurring during hydrothermal processing, which increase cellular permeability and promote water penetration into the cotyledon together with pectin solubilization. These changes generate more open and less compact matrices, leading to grain swelling and consequently a reduction in bulk density (Kinyanjui et al., 2014). The density values found in this study were lower than those

reported for several raw pulses such as white beans (*Phaseolus vulgaris*), black beans (*Phaseolus vulgaris*), mung beans (*Vigna radiata*), and butter beans (*Phaseolus lunatus*), which range from 0.79 to 0.91 g/mL (Adebo, 2026). In the case of cooked hyacinth bean, the density observed after cooking was similar to that reported for the same species soaked for 12 h and pressure-dried (0.34 g/mL) (Krishnan et al., 2025).

3.4 Techno-functional properties

The techno-functional properties of cowpea and hyacinth bean flours exhibited distinct responses to thermal processing (Table 4, Figure 2). Water-holding capacity (WHC) increased significantly in cowpea following both thermal treatments; conversely, in hyacinth bean, WHC remained unchanged after boiling and decreased after pressure cooking. Overall, WHC values (4.6–6.3 g/g) exceeded those reported for conventional pulse flours, such as lentil and common bean (3.75 and 3.60 g/g, respectively) (Belén et al., 2025), and were comparable to protein concentrates from pea, chickpea, and lentil (3.0–7.0 g/g) (J. I. Boye et al., 2010). Thermal processing alters protein conformation and starch organization, thereby modifying water retention capacity (Devkota et al., 2025; Zhang et al., 2024), although structural changes were not directly quantified in this study. Furthermore, other matrix characteristics such as particle size, total dietary fiber content, and fiber composition, also modulate WHC, meaning such variations do not always follow a predictable trend (Lucas-González et al., 2018). The high WHC observed highlights the potential application of these flours in food formulations requiring moisture retention for structural integrity and mouthfeel, such as baked goods and soups (Sreerama et al., 2012).

In contrast, oil-holding capacity (OHC) remained stable across raw and cooked flours (2.82–3.21 g/g). These values were higher than those previously reported for hyacinth bean (1.03 g/g) (Carboni et al., 2024; Krishnan et al., 2025) and for conventional pulse flours, such as lentil (0.92–1.91 g/g). Retaining OHC post-cooking is technologically advantageous for food matrices where fat entrapment contributes to texture, palatability, and flavor preservation (Kaur & Sandhu, 2010; Sreerama et al., 2012).

Thermal processing slightly reduced emulsifying capacity (EC) in both pulses ($p < 0.05$), whereas emulsion stability (ES) was preserved. Cooking can alter protein solubility and structural flexibility, affecting protein adsorption dynamics at oil–water interfaces (Lam & Nickerson, 2013; M. Li et al., 2023). The preservation of ES despite lower EC suggests that the interfacial network, once established, maintained structural integrity.

The flours demonstrated high initial foaming capacity, though foam stability (FS) declined over time (Figure 2a). Time was the primary factor influencing FS ($p<0.05$, while neither pulse species nor thermal treatment had a significant effect. Mean FS decreased from 79.46% at 5 min to 19.66% at 120 min across all samples. Consequently, thermal processing did not alter foam kinetics under the tested conditions. Discrepancies in foaming behavior among pulse flours in the literature are typically attributed to variations in protein solubility and interfacial properties, as well as differences in experimental conditions (Sreerama et al., 2012; Stone et al., 2015).

Gelation exhibited a multi-factor response, with a significant interaction among species, cooking treatment, and flour concentration ($p<0.05$) (Figure 2b). Thus, the impact

of cooking on gelation dynamics depends on both species and concentration. Crucially, all six flours formed gels at the lowest tested concentration (4%, w/v), demonstrating remarkable gelation ability compared to the minimum gelation concentrations of 12–14% typically reported for lentil flours (Kaur & Sandhu, 2010). Overall, the high WHC, OHC, and low-concentration gelation capability support the utilization of cowpea and hyacinth bean flours as functional ingredients in novel food formulations.

3.5 Phenolic content and antioxidant capacity

Total phenolic content (TPC) and antioxidant capacity exhibited clear species- and treatment-dependent responses to processing (Table 4). Significant species × treatment interactions were observed for TPC, ABTS, and DPPH ($p < 0.05$), indicating distinct thermal sensitivities between the two pulse species. In contrast, FRAP was significantly affected only by species ($p < 0.05$), with no significant treatment or interaction effects. Such assay-dependent variations are expected, as DPPH, ABTS, and FRAP operate through distinct chemical mechanisms and evaluate non-identical antioxidant parameters (Shahidi & Samarasinghe, 2025; B. Xu & Chang, 2008).

In cowpea, both thermal treatments reduced TPC and antioxidant responses (ABTS, FRAP, and DPPH) relative to raw flour, though the magnitude varied by treatment. Pressure-cooked cowpea retained higher FRAP and DPPH values than boiled samples, whereas TPC did not differ between cooking methods. Decreases in phenolic content and antioxidant capacity following aqueous thermal processing are commonly linked to the thermal degradation of bioactive compounds or the leaching of water-soluble phenolics

into the cooking medium (Conti et al., 2021; Haji et al., 2024; B. Xu & Chang, 2008). Conversely, pressure cooking can minimize phenolic losses relative to open boiling in certain pulse matrices (Melini et al., 2023), emphasizing the influence of processing parameters.

Hyacinth bean displayed greater antioxidant stability following cooking. Although TPC, ABTS, and DPPH showed treatment-dependent decreases, FRAP values remained consistent across processing conditions. This stability may stem from differences in phenolic composition, subcellular localization, and matrix interactions. Phenolics bound to cell-wall polysaccharides or dietary fiber typically exhibit higher thermal resistance and altered extractability relative to free phenolics (Giusti et al., 2019). However, because free and bound fractions were not isolated in this study, this mechanism warrants confirmation in future work.

The extent of thermal impact varied markedly between species: cowpea experienced 40–45% reductions in select antioxidant metrics, whereas hyacinth bean maintained relative stability. Matrix disruption during cooking can either promote phenolic degradation/leaching or enhance the extractability of bound fractions (Kaur et al., 2025; Liu et al., 2020), explaining the non-uniform responses observed across assays.

Overall, thermal processing did not uniformly preserve or enhance TPC and antioxidant capacity across both pulses. Cowpea exhibited higher thermal sensitivity than hyacinth bean, particularly in ABTS and DPPH assays.

3.6 Starch hydrolysis and predicted glycemic index

Starch hydrolysis profiles for both pulses exhibited a characteristic two-phase pattern, defined by a rapid initial cleavage during early digestion followed by a gradual release of glucose throughout the intestinal phase (Figure 3). The oral and gastric phases accounted for 26–36% of total starch hydrolysis across all samples, underscoring the substantial contribution of salivary α-amylase to the initial degradation of starchy food matrices (Freitas et al., 2025). During this early stage, two-way ANOVA revealed significant main effects for both pulse species and cooking method ($p<0.05$): hyacinth bean exhibited higher initial starch hydrolysis than cowpea, and pressure-cooked flours yielded higher hydrolysis levels than boiled counterparts. However, as intestinal digestion progressed, species-dependent differences in hydrolysis extent became less pronounced, whereas the impact of the cooking method persisted. At the end of intestinal digestion, equilibrium starch hydrolysis (SH_∞) ranged between 49.1% and 59.3% (Table 5), with pressure cooking consistently resulting in significantly higher SH_∞ values than conventional boiling ($p<0.05$).

Regarding digestion kinetics, starch hydrolysis approached a plateau after approximately 120 min of intestinal simulation (Figure 3). As detailed in Table 5, the kinetic constant (k) remained low across all treatments, indicating a prolonged timeframe required for α-amylase to cleave the gelatinized starch matrix into absorbable mono- and disaccharides. A significant main effect was observed for pulse species ($p<0.05$), with hyacinth bean displaying lower k values than cowpea. This indicates that while hyacinth bean underwent faster initial oral hydrolysis its subsequent intestinal digestion was

markedly slowed. This kinetic deceleration may be associated with the higher proportion of resistant starch (RS) observed in HB and its insoluble dietary fiber content, which could contribute to limiting enzymatic accessibility over extended digestion periods (Birt et al., 2013; Dhital et al., 2016)

Overall, the extent of starch hydrolysis at the end of intestinal digestion aligns with values reported for other pulses, such as common beans (30–60%) (Xu et al., 2022) and lentils (55–70%) (Duijsens et al., 2024), falling within the lower range of these benchmarks. The low overall hydrolysis suggests that limited enzymatic accessibility of starch may have persisted despite thermal processing. Previous studies have proposed that insoluble dietary fiber within intact cell walls may acts as a physical barrier that encapsulates starch granules and limits enzymatic penetration (Do et al., 2022; Parada & Aguilera, 2007b). Furthermore, interactions among starch, proteins, and cell-wall polysaccharides have been proposed to increase digesta structural compactness, restricting α-amylase accessibility (Do et al., 2022; Duijsens et al., 2024; Singh et al., 2010). However, these structural mechanisms were not directly evaluated in the present study.

The influence of cooking method on starch digestibility was evident across both species, with pressure cooking yielding higher SH_∞ values than open boiling. The higher starch hydrolysis observed in pressure-cooked samples may be associated with more extensive thermal modification of the pulse matrix. Mechanisms such as cell-wall disruption, starch gelatinization, and amylose leaching have been proposed in previous

studies as possible contributors to increased enzyme accessibility (Karunarathna et al., 2024; Yaskin Harush et al., 2025), but these mechanisms were not directly evaluated here.

The predicted glycemic index (pGI) values for all cooked samples fell within the low glycemic category (< 55) under the in vitro conditions evaluated (Table 5). These low pGI estimates directly reflect the restricted starch hydrolysis kinetics observed. For comparison, Ratnaningsih et al. (2017) reported estimated GI values ranging from 45.46 to 48.14 for starch isolated from five cowpea (*Vigna unguiculata*) varieties using *in vitro* starch digestibility methods, including the approach proposed by Goñi et al. (1997). Similarly, Rengadu et al. (2019) reported predicted GI values of 40.1–40.2 for five cowpea cultivars using an *in vitro* simulated digestion model. Although these values are lower than those obtained in the present study (49.68–50.87), direct comparisons should be made with caution because of differences in sample preparation, cultivar, processing conditions, and digestion protocols. The relatively low pGI values observed in the present study may be associated with limited enzymatic accessibility of starch within the pulse matrix. However, since cellular structure, starch molecular organization, and starch–protein–fiber interactions were not directly characterized, these mechanisms should be regarded as hypotheses rather than experimentally demonstrated explanations. Therefore, the pGI values obtained here should be interpreted as comparative *in vitro* estimates of starch digestibility rather than as evidence of glycemic control or other metabolic effects. *In vivo* studies are required to determine the actual postprandial glycemic response.

3.7 Mineral bioaccessibility

Mineral bioaccessibility following *in vitro* gastrointestinal digestion was significantly influenced by cooking conditions (Figure 4). Open boiling consistently yielded higher mineral bioaccessibility than pressure cooking, particularly for Ca, Mg, Zn, and P. In cowpea, boiled samples exhibited higher bioaccessibility for Ca (44.04%), Zn (14.58%), Mg (39.70%), and P (13.00%) than pressure-cooked samples (32.84%, 7.94%, 25.73%, and 8.51%, respectively). Hyacinth bean displayed a similar pattern for Ca, Mg, and Zn, yielding values of 35.60%, 36.03%, and 9.22% after boiling compared to 17.44%, 19.86%, and 5.88% after pressure cooking. Thus, conventional boiling favored the recovery of soluble minerals in the digested fraction.

Mineral bioaccessibility is dictated by processing conditions, chemical speciation, matrix localization, and interactions with antinutritional factors (Cilla et al., 2018; Raes et al., 2014; Suliburska & Krejpcio, 2011). Endogenous chelators, such as phytate and tannins, readily form insoluble complexes with divalent cations (Ca, Mg, Zn), reducing their solubility (Zhang et al., 2022). While antinutritional factors were not quantified here, their thermal degradation or leaching during boiling likely contributed to the enhanced mineral solubility observed.

Reported mineral bioaccessibility values in pulses vary widely due to differences in cultivars, processing protocols, and digestion models. For instance, Faria et al. (2018) reported Mg and Ca bioaccessibility values of 44.59% and 47.0% in cowpea, whereas substantial variance in Zn and Cu bioaccessibility has been noted across cooked bean

species (Bajo et al., 2026; Feitosa et al., 2018). These comparisons emphasize the importance of context when evaluating *in vitro* digestion outcomes.

Among trace minerals, Cu exhibited high relative bioaccessibility, whereas Zn consistently displayed low recovery across treatments. The low bioaccessibility of Zn underscores the distinction between total elemental concentration and the fraction accessible for absorption. Finally, these values represent the soluble mineral fraction recovered after static in vitro gastrointestinal digestion and should not be directly extrapolated to in vivo intestinal absorption or bioavailability.

3.8 Principal component analysis (PCA)

The Principal Component Analysis biplot (Figure 5a) accounted for 56.78% of the total variance (PC1 and PC2 combined), providing an exploratory representation of the relationships among the physicochemical, functional, and structural variables of the samples.

The distribution of samples along PC1 was mainly associated with botanical origin, regardless of the cooking treatment applied. Cowpea samples clustered on the negative side of PC1, strongly associated with dietary fiber fractions, essential minerals (Ca, Cu), ash content, and emulsifying capacity (EC). In contrast, hyacinth bean samples were located on the positive side of PC1, characterized by higher protein content, specific minerals (Fe, Zn, P), density, TPC, and oil holding capacity.

On the other hand, PC2 mainly reflected associations between hydrothermal treatments and the techno-functional behavior of the flours. Raw samples (C-R and HB-R) positioned toward the negative quadrant of PC2, showing a strong correlation with gelatinization parameters (Gt_8, Gt_{12}), total starch and mineral retention (Na, K). Conversely, cooked samples, shifted toward positive PC2 values. This transition was associated with

an increase in foaming and emulsion stability, soluble fiber release (SDF), and antioxidant capacity (ABTS).

Overall, these exploratory patterns suggest that botanical origin was primarily associated with PC1, whereas thermal processing was associated with PC2 and differences in the measured techno-functional properties.

Regarding effect of digestion (Figure 5b), the first principal component (PC1) explained 60% of the total variance, with sample distribution mainly associated with cooking method. Boiling treatment was associated with higher mineral bioaccessibility (Ca, Mg, Zn, P, and Cu) compared to pressure cooking (P). Pressure cooking showed lower dispersion across starch hydrolysis and bioaccessibility parameters. On the other hand, the second principal component (PC2) differentiated the response according to pulse type within the boiling treatment, with cowpea samples exhibiting higher Cu and P bioaccessibility, as well as a more pronounced starch hydrolysis kinetics compared to hyacinth bean.

Given the relatively large number of variables compared with the limited number of treatment groups, the PCA should be interpreted as an exploratory analysis of multivariate patterns rather than as confirmatory evidence of treatment effects.

4. Study limitations

Several limitations should be considered. Conventional boiling and pressure cooking differed simultaneously in temperature, processing time, pressure, and seed-to-water ratio. Therefore, this study compares the overall effects of two complete processing conditions rather than isolating the individual contribution of pressure or any other processing variable. Mechanistic explanations related to pressure, temperature, treatment duration, or water volume should consequently be interpreted as plausible hypotheses rather than

experimentally demonstrated causal mechanisms. In addition, mineral concentrations were expressed on a dry-weight basis, but cooking yield, total sample mass after cooking, and mineral content of the cooking water were not determined; thus, absolute mineral retention or loss cannot be established.

Mineral bioaccessibility represents the soluble fraction recovered after static gastrointestinal digestion and should not be equated with intestinal absorption or in vivo bioavailability. Similarly, the predicted glycemic index was determined on freeze-dried, milled flours and is an *in vitro* estimate and should not be interpreted as an *in vivo* glycemic response or as evidence of glycemic control or metabolic health effects. Phytate, tannins, protease inhibitors, lectins, and other antinutritional factors were not quantified, and phosphorus speciation was not determined. Protein digestibility and amino acid bioaccessibility were also not evaluated.

5. Conclusions

Thermal processing produced species- and attribute-dependent responses. Protein and total dietary fiber did not show significant treatment-related changes, whereas mineral concentrations, starch-related variables, antioxidant responses, and several techno-functional properties depended on the pulse and/or processing condition. Pressure-cooked flours showed higher dry-weight concentrations of several minerals than boiled flours, while boiling was associated with higher *in vitro* bioaccessibility of Ca, Mg, Zn, and P. Antioxidant responses were assay- and species-dependent, and neither cooking treatment was consistently favorable across all measured outcomes. Regarding starch digestibility, pressure cooking promoted a higher extent of equilibrium starch hydrolysis compared to

conventional boiling, although all cooked flours maintained low predicted glycemic index values (pGI < 55).

The results expand the available information on *Vigna unguiculata* and the less-studied *Lablab purpureus* as potential plant-based food ingredients. Future studies should evaluate the effects of thermal processing on antinutritional factors, protein digestibility, and amino acid bioavailability, as well as validate the functionality of these flours in food products, to further support their industrial application.

List of abbreviations

ABTS 2,2′-Azinobis-(3-ethylbenzothiazoline-6-sulfonic acid) assay

ANOVA Analysis of variance

AUC Area under the curve

C-B Boiled cowpea

C-P Pressure-cooked cowpea

C-R Raw cowpea

DPPH 2,2-Diphenyl-1-picrylhydrazyl radical scavenging assay

EC Emulsifying capacity

ES Emulsion stability

FC Foaming capacity

FRAP Ferric reducing antioxidant power assay

FS Foam stability

GAE Gallic acid equivalents

GC Gelling capacity

GOPOD Glucose oxidase–peroxidase reagent

HB-B Boiled hyacinth bean

HB-P	Pressure-cooked hyacinth bean
HB-R	Raw hyacinth bean
HI	Hydrolysis index
IDF	Insoluble dietary fiber
NRS	Non-resistant starch
OHC	Oil holding capacity
PCA	Principal component analysis
pGI	Predicted glycemic index
RS	Resistant starch
SDF	Soluble dietary fiber
SGF	Simulated gastric fluid
SIF	Simulated intestinal fluid
SSF	Simulated salivary fluid
SWC	Swelling capacity
TA	Titratable acidity
TDF	Total dietary fiber
TPC	Total phenolic content
TS	Total starch
WHC	Water holding capacity

Declarations

Ethics approval and consent to participate

Sensory evaluation for optimum cooking time determination was conducted with written informed consent from all participants. All methods and sensory evaluation procedures were performed in accordance with the relevant institutional guidelines and regulations, as well as the Declaration of Helsinki. The sensory evaluation protocol was reviewed and

approved by the Committee of Ethics and Integral Research (Comité de Ética y de Investigación Integral) through the Office of Responsible Research at Miguel Hernández University (approval code: PRL.RTA.RLG.MJCC.26)

Consent for publication.

Not applicable

Availability of data and materials.

The datasets used and/or analysed during the current study are available from the corresponding author on reasonable request.

Competing interests.

The authors declare that they have no competing interests

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Authors' contributions.

Conceptualization: M.J.C.-C., R.M.-E., and R.L.-G.; Methodology: M.J.C.-C., R.M.-E., M.V.-M., and R.L.-G.; Software: R.L.-G.; Validation: M.J.C.-C. and R.L.-G.; Formal analysis: M.J.C.-C. and R.M.-E.; Investigation: M.J.C.-C., R.M.-E., J.F.-L., and R.L.-G.; Resources: M.J.C.-C., R.M.-E., and M.V.-M.; Data curation: M.J.C.-C. and R.L.-G.; Writing—original draft preparation: M.J.C.-C.; Writing—review and editing: J.F.-L., J.Á.P.-Á., and R.L.-G.; Visualization: M.V.-M. and J.F.-L.; Supervision: R.L.-G.; Project administration: M.J.C.-C. and J.Á.P.-Á. All authors read and approved the final manuscript.

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Table 1. Cooking Conditions and Methods for cowpea and hyacinth bean

Conditions		Boiling	Pressure
Flame intensity		Medium	Medium
Water ratio		1:5 w/v	1:2 w/v
Time	Cowpea	110 min	14 min
	Hyacinth bean	135 min	25 min
Temperature		90 °C	120 °C
Pressure		-	12.5 psi

Table 2. Chemical composition of pulses samples (g/100g dw)

	C-R	C-B	C-P	HB-R	HB-B	HB-P
Moisture	10.64 ± 0.06^{a}	2.83 ± 0.09^{b}	3.58 ± 1.19^{b}	11.35 ± 0.20^{a}	3.42 ± 1.24^{b}	2.30 ± 0.44^{b}
Proteins	23.66 ± 1.37^{a}	28.80 ± 2.85^{a}	27.70 ± 2.99^{a}	26.68 ± 0.28^{a}	27.02 ± 1.66^{a}	26.41 ± 0.21^{a}
Fat	1.85 ± 0.12^{ab}	1.96 ± 0.05^{a}	1.72 ± 0.02^{b}	1.25 ± 0.06^{c}	1.08 ± 0.03^{d}	1.02 ± 0.01^{d}
TDF	24.09 ± 1.53^{a}	27.36 ± 1.18^{a}	29.30 ± 2.14^{a}	24.42 ± 0.60^{a}	27.66 ± 4.63^{a}	24.16 ± 1.48^{a}
IDF	22.58 ± 1.97^{a}	23.21 ± 0.41^{a}	26.67 ± 2.00^{a}	21.52 ± 1.01^{a}	25.87 ± 4.47^{a}	20.62 ± 0.90^{b}
SDF	1.50 ± 1.13^{a}	4.16 ± 0.83^{a}	2.63 ± 1.91^{a}	2.90 ± 1.13^{a}	1.79 ± 0.24^{a}	3.54 ± 1.96^{a}
TS	44.80 ± 0.68^{ab}	46.82 ± 1.25^{a}	41.22 ± 2.79^{ab}	39.24 ± 1.36^{b}	40.72 ± 2.74^{ab}	38.97 ± 2.46^{b}
NRS	41.68 ± 0.80^{ab}	43.81 ± 1.47^{a}	38.56 ± 2.52^{abc}	32.82 ± 1.56^{c}	36.58 ± 2.67^{bc}	34.48 ± 2.64^{c}
RS	3.12 ± 0.12^{c}	3.01 ± 0.27^{c}	2.66 ± 0.27^{c}	6.42 ± 0.20^{a}	4.13 ± 0.21^{b}	4.48 ± 0.45^{b}
Ash	3.65 ± 0.03^{a}	2.10 ± 0.25^{b}	3.22 ± 0.46^{a}	3.82 ± 0.04^{a}	2.47 ± 0.13^{b}	3.41 ± 0.14^{a}

C-R: raw cowpea; C-B: boiled cowpea; C-P: pressure-cooked cowpea; HB-R: raw hyacinth bean; HB-B: boiled hyacinth bean; HB-P: pressure-cooked hyacinth bean. TDF: total dietary fiber; IDF: insoluble dietary fiber; SDF: soluble dietary fiber; TS: total starch; NRS: non-resistant starch; RS: resistant starch. Data are expressed as mean ± standard deviation (SD) of three independent batches (n = 3). Different superscript letters within the same row indicate significant differences among individual species × treatment combinations according to Tukey's HSD test ($p < 0.05$). The two-way ANOVA included pulse species, processing treatment, and their interaction as fixed effects. Means sharing at least one superscript letter are not significantly different.

Table 3. Minerals of pulses (mg/100g dw)

	P	Na	Ca	Mg	K	Fe	Cu	Zn
C-R	187.58±9.07^{a}	1.23±0.04^{a}	82.68±2.10^{ab}	194.64±10.58^{a}	2089.79±96.45^{a}	2.36±0.06^{b}	1.06±0.17^{a}	16.77±1.10^{a}
C-B	167.82±10.55^{bc}	1.15±0.01^{b}	66.30±0.23^{c}	115.32±10.11^{c}	1254.93±12.02^{cd}	1.98±0.48^{b}	0.34±0.07^{c}	8.69±0.14^{c}
C-P	183.20±8.66^{ab}	1.20±0.01^{ab}	71.72±6.30^{bc}	147.28±12.59^{bc}	1332.15±51.88^{c}	2.29±0.26^{b}	0.55±0.01^{b}	9.66±0.98^{c}
HB-R	188.26±4.23^{a}	1.24±0.00^{a}	88.26±0.82^{a}	198.70±4.21^{a}	1782.17±18.81^{b}	3.67±0.06^{a}	0.68±0.01^{b}	8.09±0.10^{c}
HB-B	153.67±1.90^{c}	1.10±0.04^{c}	65.52±7.93^{c}	119.17±1.33^{c}	1179.22±56.33^{d}	2.09±0.03^{b}	0.56±0.01^{b}	9.98±1.05^{c}
HB-P	176.62±1.41^{ab}	1.13±0.00^{c}	93.06±9.54^{a}	171.26±28.90^{ab}	1317.42±15.90^{cd}	2.30±0.03^{b}	0.56±0.00^{b}	13.82±1.29^{b}

C-R: raw cowpea; C-B: boiled cowpea; C-P: pressure-cooked cowpea; HB-R: raw hyacinth bean; HB-B: boiled hyacinth bean; HB-P: pressure-cooked hyacinth bean. Data are expressed as mean ± standard deviation (SD) of three independent batches (n = 3). Different superscript letters within the same column indicate significant differences among individual species × treatment combinations according to Tukey's HSD test ($p < 0.05$). The two-way ANOVA included pulse species, processing treatment, and their interaction as fixed effects. Means sharing at least one superscript letter are not significantly different.

Table 4. Antioxidant Activity of pulses

Treatment	TPC (mg GAE/100 g dw)	ABTS (µmol TE/g dw)	FRAP (µmol TE/g dw)	DPPH (µmol TE/g dw)
C-R	759.88 ± 41.76^{a}	0.52 ± 0.00^{a}	0.78 ± 0.00^{ab}	0.52 ± 0.01^{a}
C-B	423.94 ± 0.04^{b}	0.40 ± 0.00^{c}	0.29 ± 0.01^{b}	0.28 ± 0.02^{c}
C-P	437.38 ± 79.75^{b}	0.43 ± 0.00^{b}	0.47 ± 0.02^{ab}	0.38 ± 0.02^{b}
HB-R	341.43 ± 22.84^{c}	0.19 ± 0.02^{d}	1.17 ± 0.54^{a}	0.26 ± 0.02^{cd}
HB-B	313.79 ± 26.14^{cd}	0.16 ± 0.01^{e}	0.97 ± 0.15^{ab}	0.24 ± 0.03^{cd}
HB-P	259.40 ± 23.65^{d}	0.12 ± 0.02^{e}	0.93 ± 0.10^{ab}	0.20 ± 0.04^{d}

C-R: raw cowpea; C-B: boiled cowpea; C-P: pressure-cooked cowpea; HB-R: raw hyacinth bean; HB-B: boiled hyacinth bean; HB-P: pressure-cooked hyacinth bean. TPC: total phenolic content; GAE: gallic acid equivalent; TE: Trolox equivalent; ABTS = 2,2′-azino-bis (3-ethylbenzothiazoline-6-sulfonic acid) method; FRAP: ferric reducing antioxidant power; DPPH: 2,2-diphenyl-1-picrylhydrazyl method. Data are expressed as mean ± standard deviation (SD) of three independent batches (n=3). Different superscript letters within the same column indicate significant differences among individual species x treatment combinations according to Tukey's HSD test ($p < 0.05$). The two-way ANOVA included pulse species, processing treatment, and their interaction as fixed effects. Means sharing at least one superscript letter are not significantly different.

Table 5. Total starch hydrolyzed at 120 and equilibrium (SH_{120} and $SH\infty$), kinetic constant (k), area under the curve (AUC), hydrolysis index (HI) and predicted glycemic index (pGI).

	SH∞ (%)	**SH_{120} (%)**	k	**AUC_{120}**	**HI_{120}**	**pGI_{120}**
C-B	49.11 ± 3.33^{b}	44.68 ± 5.88^{a}	0.022 ± 0.008^{a}	2000 ± 72^{a}	18.61 ± 0.67^{a}	49.93 ± 0.37^{a}
C-P	55.93 ± 7.44^{a}	50.78 ± 7.02^{a}	0.020 ± 0.002^{a}	2130 ± 150^{a}	19.82 ± 1.39^{a}	50.59 ± 0.76^{a}
HB-B	48.12 ± 6.65^{b}	39.55 ± 3.80^{a}	0.016 ± 0.005^{b}	1952 ± 270^{a}	18.16 ± 2.51^{a}	49.68 ± 1.38^{a}
HB-P	59.37 ± 4.02^{a}	40.88 ± 8.17^{a}	0.010 ± 0.002^{b}	2185 ± 270^{a}	20.33 ± 2.51^{a}	50.87 ± 1.38^{a}

C-B: boiled cowpea; C-P: pressure-cooked cowpea; HB-B: boiled hyacinth bean; HB-P: pressure-cooked hyacinth bean. Data are expressed as mean ± standard deviation (n = 3). Different superscript letters within the same row indicate significant differences among

treatment combinations according to two-way ANOVA followed by Tukey's HSD post-hoc test ($p < 0.05$). The ANOVA included pulse type, cooking method, and their interaction as fixed factors. No significant interaction (pulse × cooking) was observed for any parameter; therefore, superscript letters reflect pairwise comparisons among the four individual treatments. Values without letters indicate no significant differences among treatments.

Figure captations

Figure 1. Techno functional properties: a) Water holding capacity (WHC); b) Oil holding capacity; c) Emulsion capacity (EC), and d) Emulsion stability (ES) of pulse flours samples raw cowpea (C-R), boiled cowpea (C-B), pressure-cooked cowpea (C-P), raw hyacinth bean (HB-R), boiled hyacinth bean (HB-B), and pressure-cooked hyacinth bean. Data are expressed as mean ± standard deviation (n = 3). *Significant differences among the rest of samples. **Significant differences between both samples. In the graphic without* No statistically significant differences were observed among treatments according to two-way-ANOVA ($p > 0.05$) followed by Tukey's post-hoc test.

Figure 2. Time effect of techno functional properties: a) Foam stability during 120 min of storage; b) Gelation time required to achieve completely gelification at different pulse concentrations (4, 8, and 12%, w/v) of pulse flours samples: raw cowpea (C-R), boiled cowpea (C-B), pressure-cooked cowpea (C-P), raw hyacinth bean (HB-R), boiled hyacinth bean (HB-B), and pressure-cooked hyacinth bean. Data are expressed as mean ± standard deviation (n = 3). For foam stability, different letters for the overall time indicate significant differences according to Tukey's HSD test ($p < 0.05$). For gelation time, different superscript letters indicate significant differences among species × treatment ×

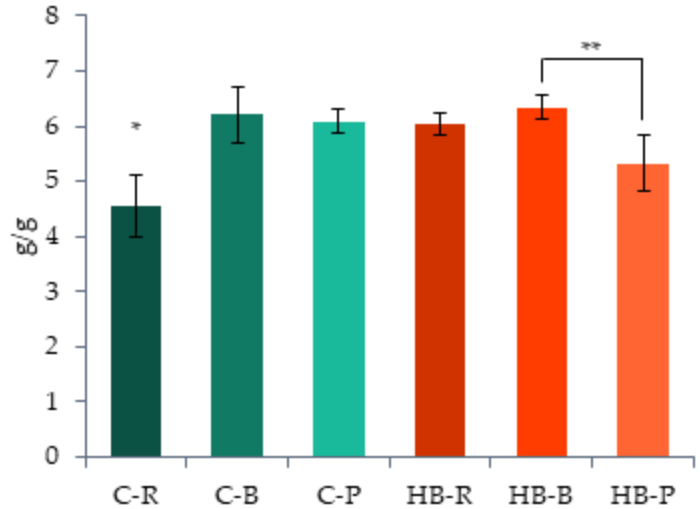
flour concentration combinations according to Tukey's HSD test ($p < 0.05$). Means sharing at least one letter are not significantly different.

Figure 3. Total starch hydrolysis rate of pulse samples: boiled cowpea (C-B), pressure-cooked cowpea (C-P), boiled hyacinth bean (HB-B), and pressure-cooked hyacinth bean, during intestinal gastrointestinal digestion. Data are expressed as mean ± standard deviation (n = 3).

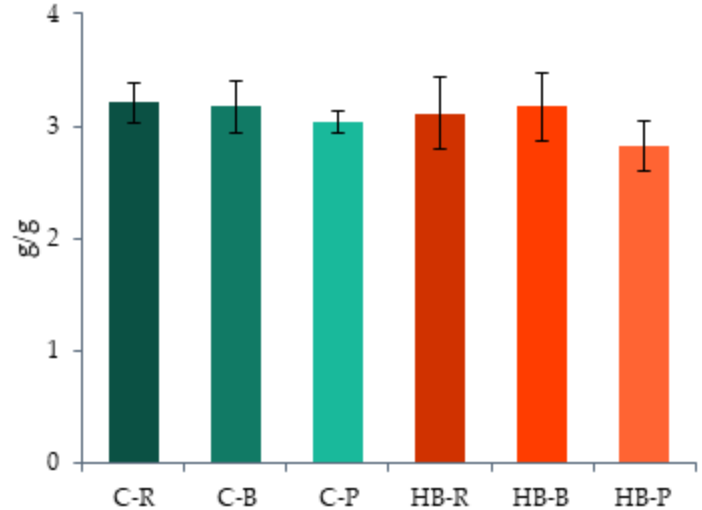
Figure 4. *In vitro* mineral bioaccessibility of cooked cowpea and hyacinth bean samples: calcium (Ca), copper (Cu), zinc (Zn), magnesium (Mg), and phosphorus (P). C-B: boiled cowpea; C-P: pressure-cooked cowpea; HB-B: boiled hyacinth bean; HB-P: pressure-cooked hyacinth bean. Values are expressed as mean ± standard deviation (SD) of three independent batches (n = 3). Different superscript letters within each mineral indicate significant differences among species × cooking treatment combinations according to Tukey's HSD test ($p < 0.05$). Means sharing at least one letter are not significantly different.

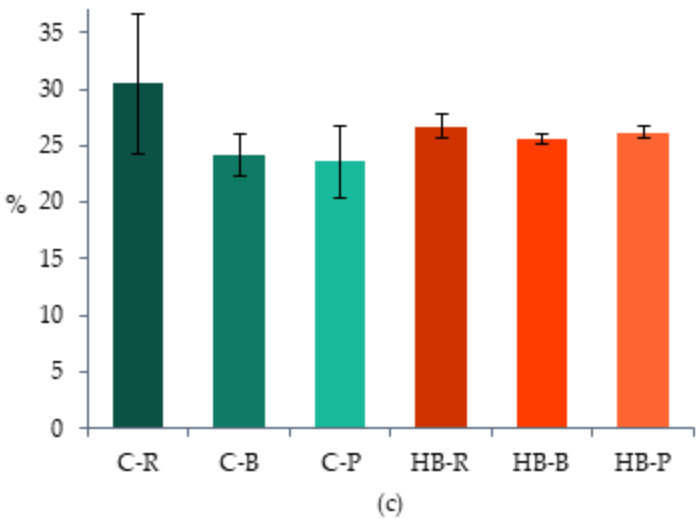
Figure 5. Principal Component Analysis (PCA) biplot of (a) chemical, mineral profile, and techno functional properties of the samples. (b) Starch hydrolysis, starch kinetic, and mineral bioaccessibility. The vectors represent the loadings of the analyzed variables, while the filled circles indicate the individual scores of the sample groups. C-R: raw cowpea; C-B: boiled cowpea; C-P: pressure-cooked cowpea; HB-R: raw hyacinth bean; HB-B: boiled hyacinth bean; HB-P: pressure-cooked hyacinth bean. TPC: total phenolic content; ABTS, DPPH, FRAP, antioxidant capacity assays; TDF, total dietary fiber; IDF, insoluble dietary fiber; SDF: soluble dietary fiber; Den.: density; WHC: water holding capacity; OHC: oil holding capacity; EC: emulsifying capacity; EE, emulsion stability; Gt: Gelation time at different concentrations; FE: foaming stability at different time; RS:

resistant starch; NRS: non-resistant starch; TS: total starch. $SH_{120,\infty}$**:** starch hydrolysis (120 min, equilibrium); pGI: predicted glycemic index; HI: hydrolysis index; k: kinetic constant; Cu, Zn, Ca, Mg, P_{BI}**:** element bioaccessibility index.

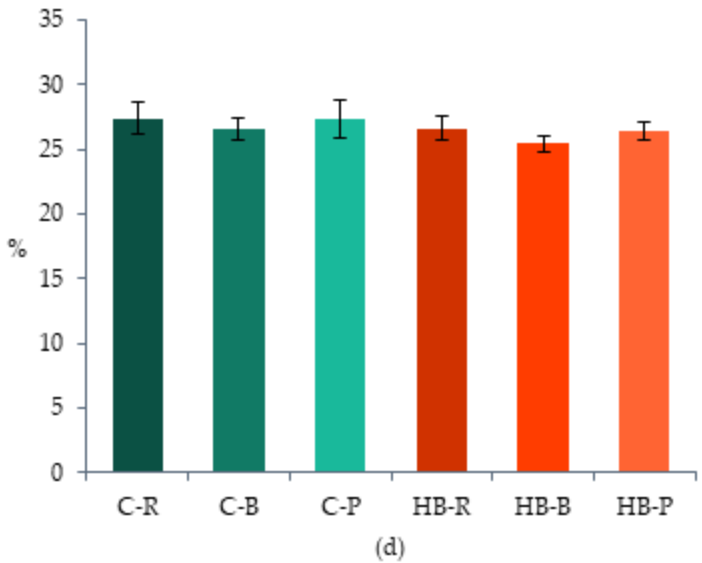

8
7
6
5
4
3
2
1
0
g/g
*
**
C-R
C-B
C-P
HB-R
HB-B
HB-P

(a)

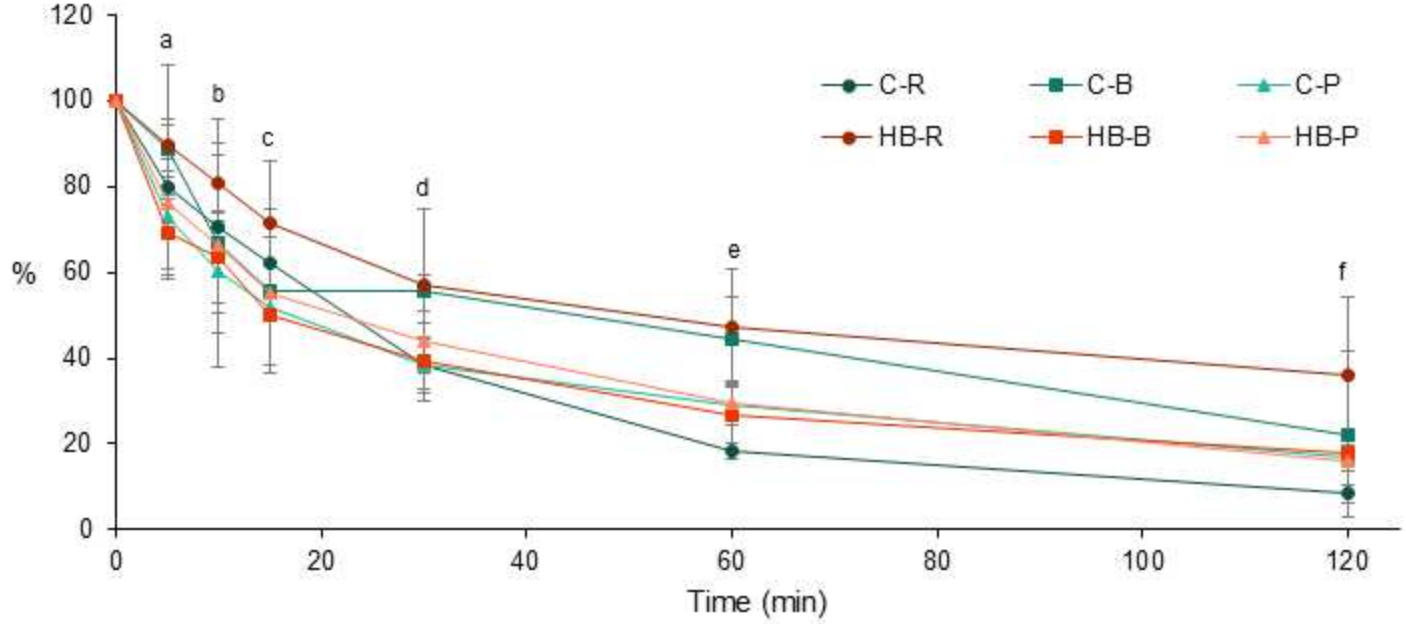

4
3
2
1
0
g/g
C-R
C-B
C-P
HB-R
HB-B
HB-P


35
30
25
20
15
10
5
0
%
C-R
C-B
C-P
HB-R
HB-B
HB-P

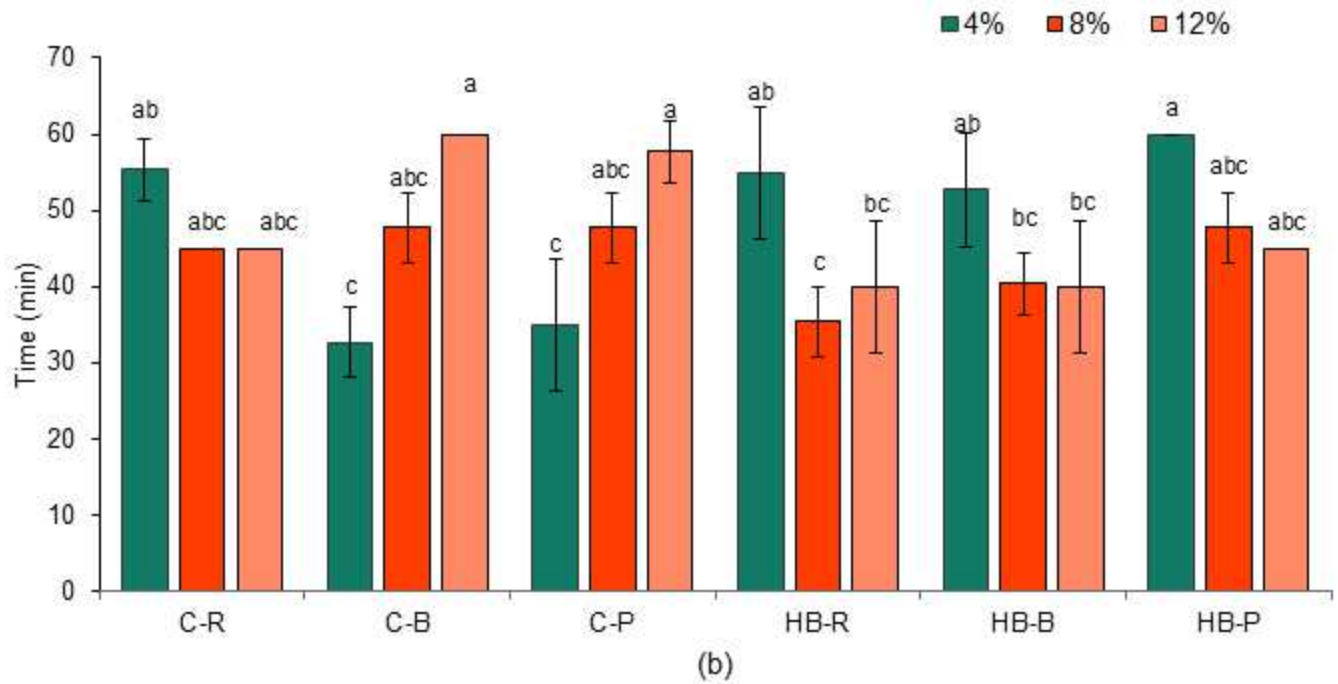
(c)


35
30
25
20
15
10
5
0
%
C-R
C-B
C-P
HB-R
HB-B
HB-P

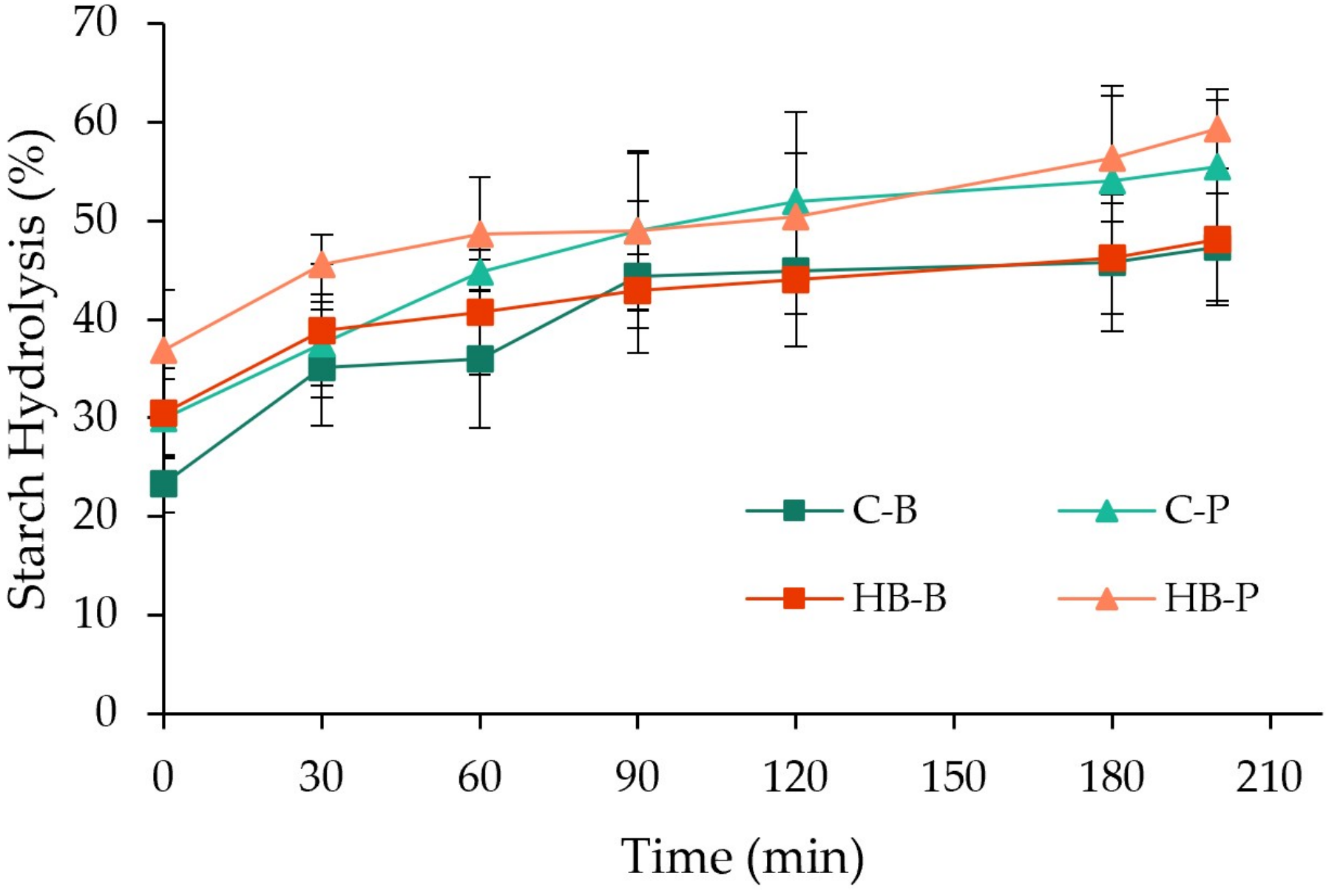
(d)

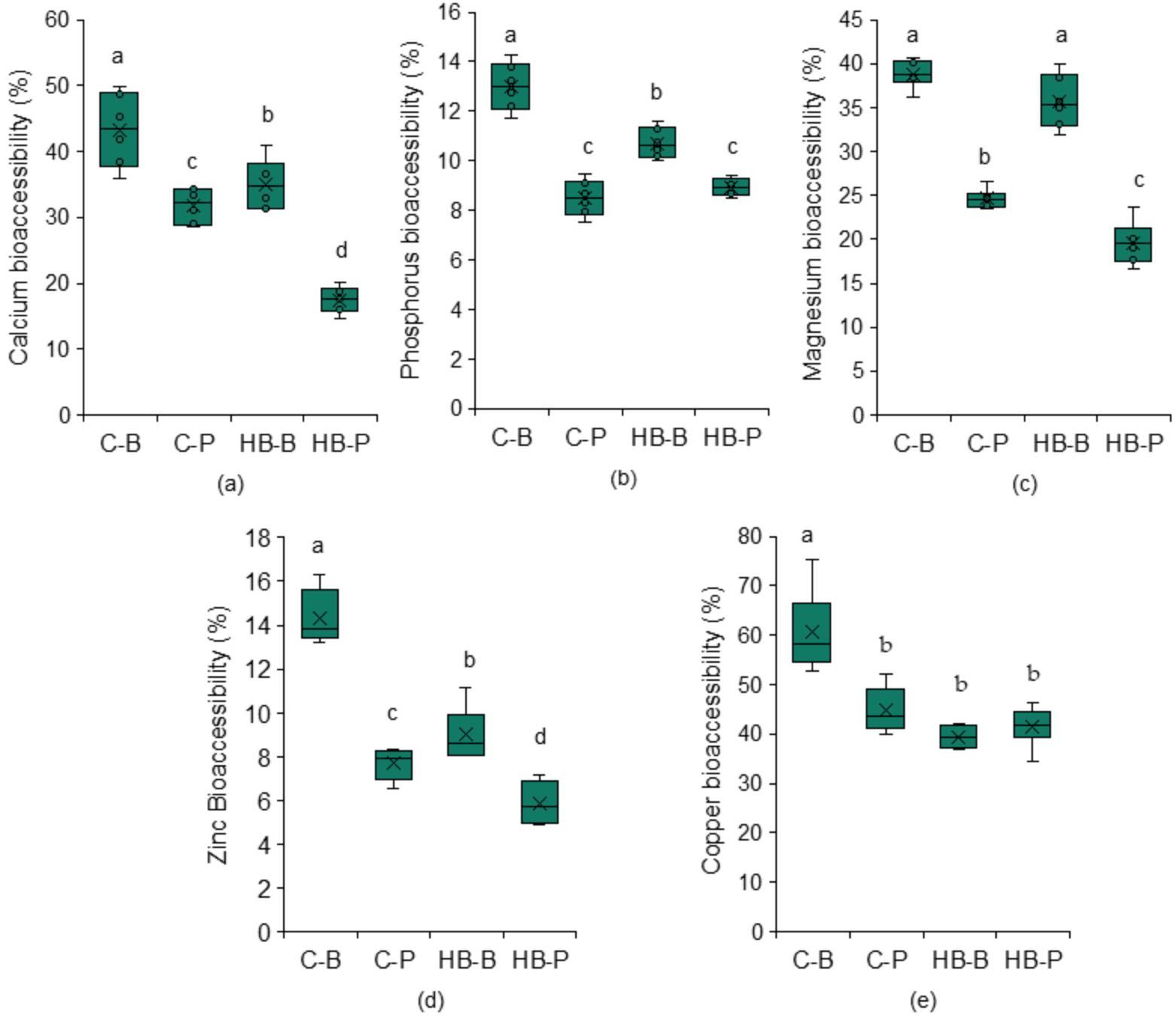

120
100
80
60
40
20
0
%
0
20
40
60
80
100
120
Time (min)
a
b
c
d
e
f
C-R
C-B
C-P
HB-R
HB-B
HB-P

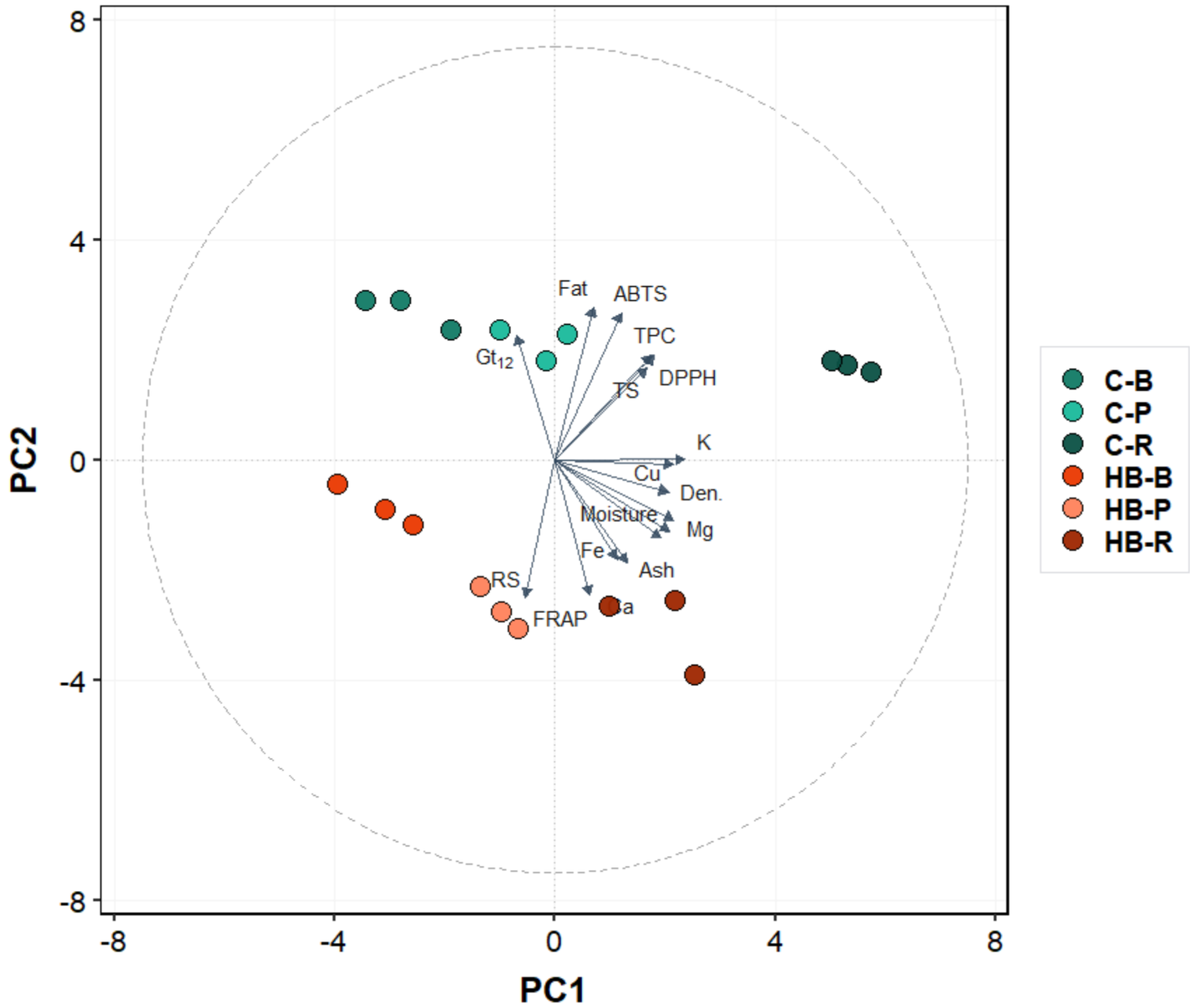
(a)

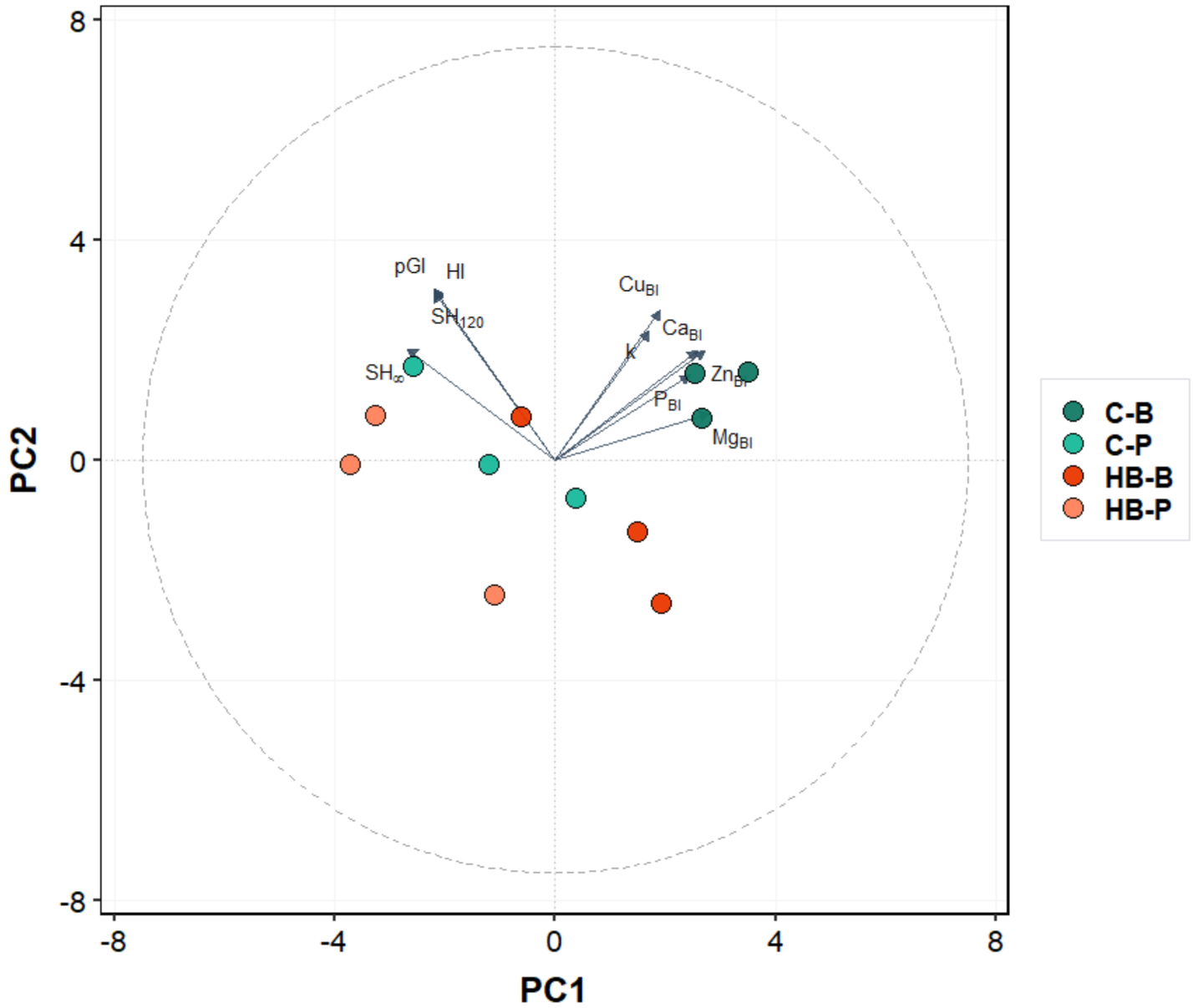

4%
8%
12%
70
60
50
40
30
20
10
0
Time (min)
ab
abc
abc
c
abc
a
c
abc
a
ab
c
bc
ab
bc
bc
a
abc
abc
C-R
C-B
C-P
HB-R
HB-B
HB-P

(b)


Starch Hydrolysis (%)
70
60
50
40
30
20
10
0
0
30
60
90
120
150
180
210
Time (min)
C-B
C-P
HB-B
HB-P


Calcium bioaccessibility (%)
60
50
40
30
20
10
0
a
c
b
d
C-B
C-P
HB-B
HB-P
(a)
Phosphorus bioaccessibility (%)
16
14
12
10
8
6
4
2
0
a
c
b
c
C-B
C-P
HB-B
HB-P
(b)
Magnesium bioaccessibility (%)
45
40
35
30
25
20
15
10
5
0
a
b
a
c
C-B
C-P
HB-B
HB-P
(c)
Zinc Bioaccessibility (%)
18
16
14
12
10
8
6
4
2
0
a
c
b
d
C-B
C-P
HB-B
HB-P
(d)
Copper bioaccessibility (%)
80
70
60
50
40
30
20
10
0
a
b
b
b
C-B
C-P
HB-B
HB-P
(e)


8
4
0
-4
-8
PC2
-8
-4
0
4
8
PC1
Fat
ABTS
TPC
DPPH
TS
K
Cu
Den.
Moisture
Mg
Fe
Ash
RS
FRAP
Gt12
C-B
C-P
C-R
HB-B
HB-P
HB-R


8
4
0
-4
-8
PC2
-8
-4
0
4
8
PC1
pGI
HI
SH120
SH∞
CuBI
CaBI
K
ZnBI
PBI
MgBI
C-B
C-P
HB-B
HB-P

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