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Original Paper

Exploring Native Ecuadorian Legumes as Sustainable Sources of Antioxidants and Essential Amino Acids

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Key Words
Underutilized legumes • Protein quality • Antioxidant capacity • Phytate:mineral ratios • Sustainable nutrition

Abstract
Background/Aims: Underutilized native legumes may contribute to the development of sustainable, nutrient-dense foods with potential relevance to malnutrition and diet-related non-communicable diseases. ***Methods:*** This study evaluated the nutritional and functional profile of five native Ecuadorian legumes (*Cajanus cajan*, *Lablab purpureus*, *Phaseolus lunatus* baby lima, *Phaseolus lunatus* big lima, and *Vigna unguiculata*) through proximate composition, dietary fiber, mineral content, antioxidant capacity, amino acid profiles, amino acid scores (AAS), and phytate molar ratios. ***Results:*** *Lablab purpureus* showed the highest amino acid score (166.30%), followed by *P. lunatus* baby lima (159.46%) and *V. unguiculata* (156.82%), and all species exceeded the FAO/WHO indispensable amino acid reference pattern for older children, adolescents, and adults. *Cajanus cajan* was characterized by high dietary fiber (31.44 g/100 g) and calcium contents (5750 mg/kg), whereas *Lablab purpureus* and *Vigna unguiculata* showed higher iron and magnesium contents, together with antioxidant responses associated with phenolic compounds. Although phytate molar ratios suggested potential constraints on non-heme iron bioavailability, the comparatively low phytate ratios indicated lower predicted

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interference with magnesium availability. Principal component analysis explained 77.6% of the total variance and revealed differentiated nutritional profiles among species. ***Conclusion:*** These findings support a cautious translational interpretation of underutilized Ecuadorian legumes as differentiated plant food matrices in which phenolic compounds, dietary fiber, amino acids, and minerals may contribute to redox balance, gut barrier physiology, protein adequacy, and micronutrient nutrition.

Introduction

Malnutrition in Ecuador remains a dual public health challenge in which chronic undernutrition coexists with overweight, obesity, and diet-related non-communicable diseases. This combined burden supports the need for food-based strategies that provide protein, dietary fiber, minerals, and bioactive compounds without increasing dependence on highly processed foods or environmentally costly protein sources [1, 2]. Legumes are particularly relevant in this context because they combine moderate-to-high protein density, complex carbohydrates, dietary fiber, minerals, and antioxidant phytochemicals within a single plant-based food matrix [3, 4]. Beyond their macronutrient contribution, legumes contain phenolic compounds, flavonoids, dietary fiber fractions, phytates, minerals, and amino acids that may interact with human physiology through multiple biochemical pathways. Phenolic compounds may contribute to cellular redox homeostasis through direct radical-scavenging activity and by modulating endogenous antioxidant and inflammatory responses, including pathways related to Nrf2/ARE and NF-κB signaling [5, 6]. Dietary fiber can influence gut microbiota metabolism and the production of short-chain fatty acids, metabolites associated with intestinal barrier function and immunometabolic regulation [7, 8]. In parallel, amino acid composition determines the capacity of a protein source to meet indispensable amino acid requirements, whereas minerals such as calcium, magnesium, and iron are physiologically essential but their nutritional utilization is strongly influenced by food-matrix interactions, particularly the chelating activity of phytate [9, 10]. Ecuador harbors a diversity of native and underutilized legumes that remain insufficiently characterized from a nutritional physiology perspective. Species such as *Cajanus cajan* —pigeon pea—, *Lablab purpureus* —hyacinth bean—, *Vigna unguiculata* —cowpea—, and *Phaseolus lunatus* —lima bean— are locally available species with differentiated compositional attributes. Existing literature supports the nutritional relevance of legumes; however, accession-specific datasets are required to determine whether these species contribute primarily as protein sources, fiber- and calcium-rich ingredients, antioxidant-associated matrices, or starch-dense foods [3, 4]. Therefore, the objective of this study was to evaluate the nutritional and functional profile of five native Ecuadorian legume accessions through proximate analysis, dietary fiber fractions, mineral composition, phytate content, antioxidant assays, amino acid profiling, and multivariate statistics. In response to the need for a stronger physiological interpretation, the revised manuscript further integrates amino acid score analysis according to FAO/WHO reference patterns, phytate molar ratios, and a mechanistic discussion linking the measured compositional traits with plausible pathways related to redox-inflammatory regulation, gut barrier physiology, metabolic regulation, protein adequacy, and mineral bioavailability [9, 11].

Materials and Methods

Samples

Five legume accessions were collected from different regions of Ecuador: *Cajanus cajan* (gandul; Manabí), *Phaseolus lunatus* baby lima (habichuela; Manabí), *Phaseolus lunatus* big lima (haba pallar; Manabí), *Lablab purpureus* (zarandaja; Loja), and *Vigna unguiculata* (firigüero; Loja). Samples were oven-dried at 50 °C for 24 h, ground, and sieved to 35-70 mesh. Flours were stored in airtight containers at room temperature until analysis.

Proximate Composition and dietary fiber

Moisture, total protein, ash, and crude fat contents were determined according to AOAC Official Methods 925.10, 920.87, 923.03, and 920.85, respectively [12].Total dietary fiber (TDF) and insoluble dietary fiber (IDF) were determined using the enzymatic–gravimetric method AOAC 991.43. Soluble dietary fiber (SDF) was calculated as the difference between TDF and IDF [12].

Mineral Content, Reducing Sugars, Total Starch and Vitamin E

The concentrations of iron (Fe), calcium (Ca), and magnesium (Mg) were determined according to official AOAC protocols. Fe was quantified via AOAC method 999.10, while Ca and Mg were determined simultaneously using an atomic absorption spectrometer (PG Instruments, model AA500) following AOAC method 985.35 [12]. Reducing sugars before and after acid hydrolysis were quantified using the 3,5-dinitrosalicylic acid (DNS) colorimetric method as described by Miller [13], with absorbance measured at 540 nm. Total starch content was determined enzymatically according to the protocol described by Holm et al. [14], which involves hydrolyzing starch to glucose and subsequent colorimetric quantification. Vitamin E content, expressed as α-tocopherol and α-tocotrienol, was determined by high-performance liquid chromatography (HPLC) according to the method described by Piironen et al. [15].

Phytate Content

Phytate (inositol hexaphosphate) content was determined using anion-exchange chromatography according to the method of Harland and Oberleas [16].

Determination of Total Phenolic Content and Antioxidant Capacity

Antioxidant compounds were extracted using acidified solvents (pH ≈ 2) following the procedures of Saura-Calixto [7] and Thaipong et al [17].. Total phenolic content (TPC) was determined using the Folin–Ciocalteu reagent, as described by Alhakmani et al [18].. The method was adapted for a 96-well microplate, and absorbance was measured at 725 nm. Results are expressed as mg of gallic acid equivalents (GAE) per gram of sample. ***Antioxidant capacity was evaluated through three complementary assays:***

- DPPH: Radical scavenging activity was determined at 515 nm according to Brand-Williams et al. [19], with modifications by Thaipong et al. [17].
- ABTS: The radical cation decolorization assay was performed at 734 nm following Arnao et al. [20].
- FRAP: Ferric reducing antioxidant power was measured at 593 nm according to Benzie and Strain [21].

Amino Acid Profile

Amino acid profiles were determined by reverse-phase high-performance liquid chromatography (RP-HPLC) using a Waters Alliance 2695 system. Samples were subjected to acid hydrolysis, followed by pre-column derivatization with 6-aminoquinolyl-N-hydroxysuccinimidyl carbamate (AQC). Separation was performed on an XBridge BEH C18 column (5 μm, 4.6 × 150 mm) using an acetonitrile/water/sodium acetate buffer gradient at a flow rate of 1.0 mL/min. Detection was carried out by fluorescence (λ_ex = 249 nm; λ_em = 395 nm), and quantification was based on external standards.

Protein Quality and Limiting Amino Acids

Protein quality was estimated by calculating amino acid scores (AAS) according to the FAO/WHO reference pattern for older children, adolescents and adults [9, 22]. Amino acids reported as g/100 g dry sample were converted to mg amino acid per g protein as: mg amino acid/g protein = (g amino acid/100 g sample ÷ g protein/100 g sample) × 1000. Sulfur amino acids (SAA) were calculated as methionine + cysteine, and aromatic amino acids (AAA) as phenylalanine + tyrosine. AAS was calculated as: AAS = measured amino acid content (mg/g protein) ÷ FAO/WHO reference value (mg/g protein). The limiting amino acid was the indispensable amino acid with the lowest AAS. This compositional index was used to evaluate amino acid adequacy [9, 22].

Phytate:mineral molar ratios

Phytate:Fe, phytate:Ca and phytate:Mg molar ratios were calculated from the experimentally determined phytate and mineral contents after conversion to molar units using the corresponding molecular

or atomic weights. These ratios were used as predictive indicators of mineral bioavailability, recognizing that they estimate potential chelation effects rather than measuring human absorption directly [10, 23].

Statistical and multivariate analysis

Analyses were performed in triplicate and results are expressed as mean ± standard deviation. Principal component analysis (PCA) was applied to integrate the nutritional, antioxidant, mineral and amino acid variables and to identify species-specific compositional niches [24]

Results

Proximate composition, mineral density, and ingredient differentiation

The proximate composition (Table 1) confirmed that the evaluated accessions are relevant plant protein sources, with protein concentrations from 18.67 to 21.59 g/100 g. *L. purpureus*, *P. lunatus* and *V. unguiculata* showed the highest protein concentrations, whereas *C. cajan* was characterized by the highest total dietary fiber content (31.44 g/100 g). Mineral profiles were highly differentiated. *C. cajan* showed a markedly high calcium concentration (5750 mg/kg), whereas *L. purpureus* and *V. unguiculata* contained higher iron and magnesium.

Antioxidant capacity

The antioxidant assays showed clear species-dependent differences (Fig. 1). *V. unguiculata* and *L. purpureus* exhibited the highest responses across radical-scavenging and reducing-power assays, consistent with their total phenolic content [7, 17, 19–21].

Table 1. Chemical Composition of Raw Ecuadorian Legumes. * Different letters show statistically significant differences, LOD, limit of detection. Analysis per gram of dry matter

Analyte	Unit	*Cajanus cajan L. Millsp.*	*Lablab purpureus L. Sweet*	*Phaseolus lunatus L. baby lima*	*Phaseolus lunatus L. big lima*	*Vigna unguiculata L. Walp.*
Moisture	g/100 g	9.11 ± 0.20 c	8.84 ± 0.11 c	8.95 ± 0.14 c	9.71 ± 0.25 b	10.61 ± 0.06 a
Protein	g/100 g	18.67 ± 0.29 b	21.44 ± 0.44 a	21.15 ± 0.15 a	21.29 ± 0.00 a	21.59 ± 0.30 a
Fat	g/100 g	1.71 ± 0.15 a	0.75 ± 0.01 c	1.55 ± 0.10 ab	0.87 ± 0.02 c	1.41 ± 0.04 b
Ash	g/100 g	3.86 ± 0.02 a	3.40 ± 0.05 a	3.58 ± 1.24 a	4.12 ± 0.03 a	3.45 ± 0.15 a
Total dietary fiber	g/100 g	31.44 ± 0.88 a	27.80 ± 0.45 b	22.07 ± 0.07 c	21.41 ± 0.16 c	22.72 ± 0.53 c
Insoluble dietary fiber	g/100 g	26.98 ± 1.10 a	24.50 ± 0.10 b	18.59 ± 0.58 c	17.85 ± 0.43 c	18.60 ± 0.53 c
Soluble dietary fiber	g/100 g	4.47 ± 0.57 a	3.31 ± 0.47 b	3.47 ± 0.53 ab	3.56 ± 0.27 ab	4.11 ± 0.14 ab
Starch	g/100 g	41.67 ± 0.69 b	41.39 ± 2.40 b	56.00 ± 3.46 a	41.84 ± 2.05 b	38.04 ± 0.81 b
Total sugars	g/100 g	2.49 ± 0.03 d	2.03 ± 0.05 e	2.79 ± 0.04 c	4.50 ± 0.03 a	4.04 ± 0.09 b
Reducing sugars	g/100 g	0.4 ± 0.04 b	0.2 ± 0.01 c	0.6 ± 0.01 a	0.5 ± 0.00 b	0.7 ± 0.02 a
Calcium	mg/kg	5750 ± 255 a	1117 ± 54 b	1189 ± 77 b	138 ± 8 c	442 ± 20 c
Iron	mg/kg	42 ± 2 b	69 ± 2 a	61 ± 6 a	43 ± 4 b	61 ± 2 a
Magnesium	mg/kg	1209 ± 25 a	1795 ± 215 b	1865 ± 20 b	1406 ± 96 c	2277 ± 37 c
Vitamin E	mg/kg	2.8 ± 0.06 a	<LOD	<LOD	1.5 ± 0.10 b	2.8 ± 0.10 a
Phytates	mg/g	7.1 ± 0.61 c	10.5 ± 0.53 a	8.6 ± 0.79 b	6.6 ± 0.00 c	11.6 ± 0.29 a

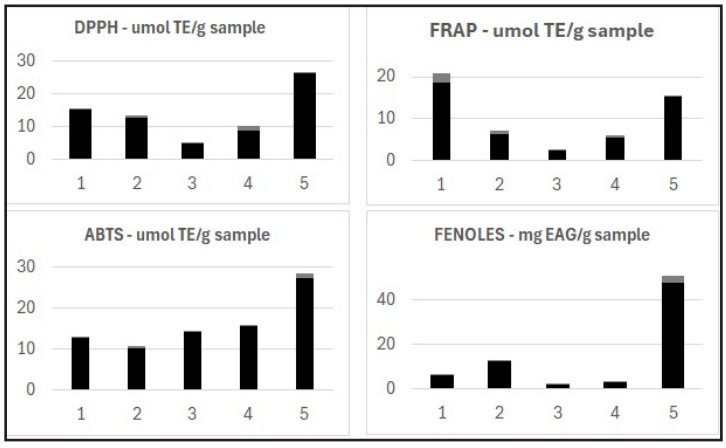

Fig. 1. Antioxidant capacity of raw legume flours (a) DPPH, (b) FRAP, (c) ABTS, (d) total polyphenol content. 1. *Cajanus cajan L. Millsp* – Gandul, 2. *Lablab purpureus L. Sweet* – Zarandaja, 3. *Phaseolus lunatus L. baby lima* – Habichuela, 4. *Phaseolus lunatus L. big lima* – Haba pallar, 5. *Vigna unguiculata L. Walp* – Firigüero. Analyses were performed on a dry matter basis.

Dietary fiber

Dietary fiber represented one of the most discriminating variables in the dataset. *C. cajan* showed the highest total and insoluble dietary fiber concentrations, while all accessions contained substantial fiber fractions.

Amino acid profile and amino acid score

The amino acid profile (Table 3) confirmed that the evaluated legumes contain nutritionally relevant concentrations of indispensable amino acids. *L. purpureus* and *V. unguiculata* were particularly rich in lysine. AAS analysis further characterized protein quality (Table 2). All legumes exceeded the FAO/WHO reference pattern for older children, adolescents, and adults, with the lowest AAS values ranging from 1.36 to 1.66. *C. cajan* presented leucine as the limiting amino acid, whereas valine was the limiting amino acid in *L. purpureus*, *P. lunatus* baby lima, *P. lunatus* big lima and *V. unguiculata*. Importantly, all limiting amino acid scores remained above 1.00.

Table 2. Limiting amino acids and lowest amino acid scores relative to the FAO/WHO reference pattern for older children, adolescents and adults. Values are mean ± standard deviation where replicate calculations were available. Different letters indicate significant differences

Species	Limiting amino acid	Lowest AAS (ratio)	Lowest AAS (% of FAO/WHO pattern)
Cajanus cajan	Leucine	1.36	136.21 ± 3.02 c
Lablab purpureus	Valine	1.66	166.30 ± 4.61 a
Phaseolus lunatus baby lima	Valine	1.60	159.46 ± 0.73 ab
Phaseolus lunatus big lima	Valine	1.54	153.56 ± 0.60 b
Vigna unguiculata	Valine	1.57	156.82 ± 2.14 b

Table 3. Amino acid content of raw legumes. * Different letters indicate statistically significant differences between matrices., LOD, limit of detection. Analysis per gram of dry matter

Analyte	Unit	*Cajanus cajan L. Millsp.*	*Lablab purpureus L. Sweet*	*Phaseolus lunatus L. baby lima*	*Phaseolus lunatus L. big lima*	*Vigna unguiculata L. Walp.*
Aspartic acid	g/100 g	1.66 ± 0.01 a	2.56 ± 0.01 d	2.30 ± 0.00 c	2.32 ± 0.02 c	2.34 ± 0.01 c
Serine	g/100 g	1.07 ± 0.00 a	1.48 ± 0.02 c	1.46 ± 0.02 bc	1.47 ± 0.02 bc	1.33 ± 0.02 b
Glutamic acid	g/100 g	2.30 ± 0.00 b	2.61 ± 0.01 d	2.03 ± 0.00 a	2.01 ± 0.00 a	2.56 ± 0.01 c
Histidine	g/100 g	0.91 ± 0.01 a	1.08 ± 0.01 d	0.98 ± 0.01 b	0.96 ± 0.01 b	1.05 ± 0.01 c
Glycine	g/100 g	0.94 ± 0.03 a	1.22 ± 0.02 d	1.12 ± 0.01 c	1.09 ± 0.01 bc	1.18 ± 0.01 cd
Arginine	g/100 g	1.00 ± 0.01 a	1.47 ± 0.01 d	1.16 ± 0.01 b	1.14 ± 0.01 b	1.40 ± 0.01 c
Threonine	g/100 g	0.92 ± 0.02 a	1.18 ± 0.02 b	1.16 ± 0.01 b	1.18 ± 0.01 b	1.17 ± 0.02 b
Alanine	g/100 g	1.03 ± 0.02 a	1.30 ± 0.01 d	1.19 ± 0.01 c	1.17 ± 0.01 bc	1.24 ± 0.01 cd
Proline	g/100 g	0.99 ± 0.01 a	1.20 ± 0.01 c	1.05 ± 0.01 b	1.05 ± 0.00 b	1.13 ± 0.00 bc
Cysteine	g/100 g	0.56 ± 0.00 a	1.29 ± 0.00 e	0.84 ± 0.02 c	0.75 ± 0.01 b	1.10 ± 0.01 d
Tyrosine	g/100 g	0.55 ± 0.01 a	0.72 ± 0.02 d	0.63 ± 0.01 b	0.61 ± 0.00 b	0.67 ± 0.01 c
Valine	g/100 g	1.06 ± 0.01 a	1.39 ± 0.01 d	1.32 ± 0.02 c	1.28 ± 0.01 bc	1.32 ± 0.00 c
Methionine	g/100 g	0.60 ± 0.00 a	0.72 ± 0.01 c	0.68 ± 0.01 b	0.67 ± 0.01 b	0.74 ± 0.00 c
Lysine	g/100 g	1.35 ± 0.02 a	1.78 ± 0.02 d	1.61 ± 0.01 c	1.58 ± 0.02 c	1.72 ± 0.01 d
Isoleucine	g/100 g	0.95 ± 0.01 a	1.25 ± 0.01 c	1.24 ± 0.02 c	1.18 ± 0.01 b	1.16 ± 0.02 b
Leucine	g/100 g	1.50 ± 0.01 a	2.34 ± 0.04 c	2.03 ± 0.01 b	2.25 ± 0.02 b	2.23 ± 0.03 c
Phenylalanine	g/100 g	1.55 ± 0.01 a	1.37 ± 0.01 b	1.35 ± 0.02 b	1.27 ± 0.01 b	1.43 ± 0.01 c

Phytate:mineral molar ratios

Phytate:mineral molar ratios revealed marked differences among species (Table 4). All evaluated legumes showed phytate:Fe ratios above the critical threshold associated with reduced non-heme iron availability, with *V. unguiculata* presenting the highest value [10, 23, 28, 29]. In contrast, *C. cajan* showed the lowest phytate:Ca ratio because of its very high

calcium concentration. *P. lunatus* big lima and *V. unguiculata* exhibited the highest phytate:Ca ratios. Phytate:Mg ratios were comparatively low and showed less variation among species.

Multivariate integration

Principal component analysis integrated compositional, antioxidant, mineral, phytate and amino acid variables, explaining 77.6% of the total variance in the first two components (Figure 2). PC1 separated protein- and amino acid-rich matrices from the fiber- and calcium-rich profile of Cajanus cajan, whereas PC2 differentiated antioxidant-associated variables from starch-dominant profiles.

Conceptual physiological model

A conceptual model summarizing the biological interpretation of the dataset is presented in Fig. 3.

Table 4. Phytate:mineral molar ratios of raw legumes. * Values are mean ± standard deviation (n = 3) on a dry matter basis. Different letters within the same column indicate significant differences

Legumes	Phytate:Fe	Phytate:Ca	Phytate:Mg
Cajanus cajan	12.90 ± 0.73 ab	0.07 ± 0.01 d	0.20 ± 0.01 a
Lablab purpureus	11.66 ± 0.35 ab	0.52 ± 0.04 c	0.20 ± 0.03 a
P. lunatus baby lima	11.01 ± 2.03 b	0.40 ± 0.02 c	0.15 ± 0.01 a
P. lunatus big lima	11.67 ± 1.09 ab	2.63 ± 0.17 a	0.16 ± 0.01 a
Vigna unguiculata	14.27 ± 0.60 a	1.42 ± 0.06 b	0.17 ± 0.01 a

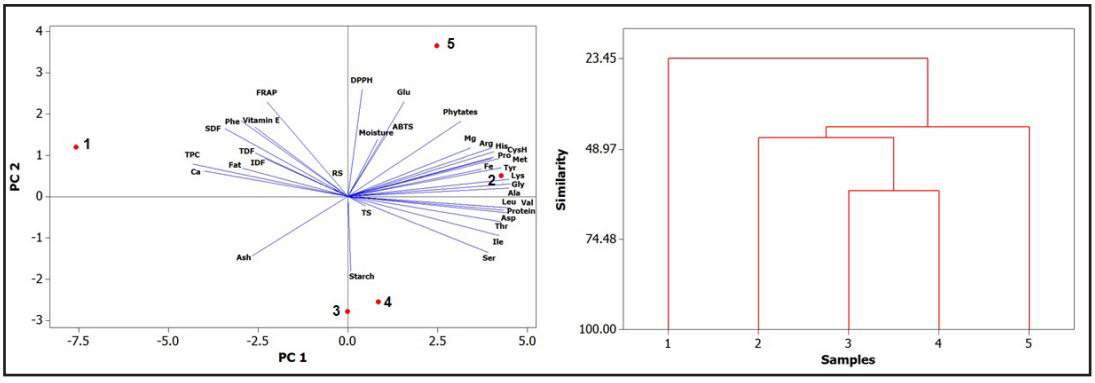

Fig. 2. Multivariate analysis of raw legume flours: (a). Principal Component Analysis (PCA), (b). Analysis multivariate segregation 1. *Cajanus cajan L. Millsp* – Gandul, 2. *Lablab purpureus L. Sweet* – Zarandaja, 3. *Phaseolus lunatus L. baby lima* – Habichuela, 4. *Phaseolus lunatus L. big lima* – Haba pallar, 5. *Vigna unguiculata L. Walp* – Firigüero.

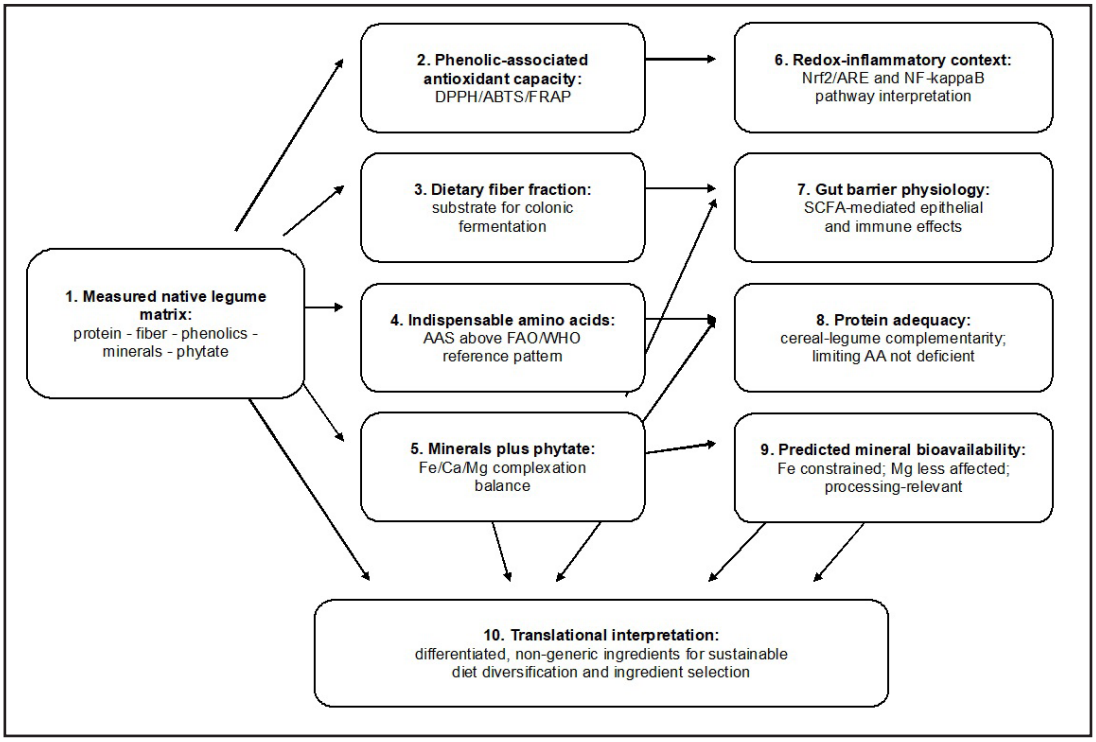

Fig. 3. Conceptual mechanistic model linking measured legume matrix components with physiologically relevant domains. The Fig. summarizes plausible biological interpretation of the compositional data.

Discussion

The evaluated Ecuadorian legumes exhibited distinct compositional characteristics, indicating that they should not be considered interchangeable food ingredients. While *L. purpureus*, *P. lunatus*, and *V. unguiculata* were characterized by higher protein concentrations, *C. cajan* was distinguished by its high dietary fiber and calcium contents. This separation suggests different nutritional applications, with some species being more suitable for protein enrichment and *C. cajan* representing a fiber- and calcium-dense ingredient. Although mineral concentrations differed considerably among species, mineral content alone does not predict nutritional usefulness because phytate can bind polyvalent cations and reduce mineral accessibility in plant-based diets [10, 23]. Consequently, phytate:mineral molar ratios provide a more physiologically meaningful interpretation than total mineral concentrations alone. The higher antioxidant activities observed in *V. unguiculata* and *L. purpureus* are consistent with their elevated phenolic contents. These *in vitro* assays should not be interpreted as evidence of biological efficacy but rather as indicators that these flours contain redox-active compounds capable of electron transfer, hydrogen atom donation and metal-chelating reactions under assay conditions [7, 17, 19–21]. Previous studies have associated dietary polyphenols with modulation of oxidative stress and inflammatory signaling, including Nrf2/ARE and NF-κB pathways [6, 25, 26]. Although the present study did not investigate these mechanisms experimentally, the observed antioxidant profile is consistent with this mechanistic framework. Dietary fiber emerged as another important distinguishing characteristic. The elevated fiber content of *C. cajan* may influence intestinal transit, microbial fermentation and the production of short-chain fatty acids, particularly butyrate, which have been associated with epithelial barrier function, immune regulation and inflammatory control [8]. In addition, phenolic compounds frequently remain associated with insoluble cell-wall structures and may become available after microbial fermentation,

emphasizing that the fiber–phenolic matrix should be considered as an integrated food structure rather than isolated components [7]. The amino acid composition further supports the nutritional value of these legumes. The relatively high lysine concentrations observed in *L. purpureus* and *V. unguiculata* may complement cereal-based diets, in which lysine is frequently the limiting amino acid [9, 22, 27]. Moreover, all species exceeded the FAO/WHO indispensable amino acid reference pattern for older children, adolescents and adults. Although leucine or valine represented the limiting amino acid depending on the species, all amino acid scores remained above 1.00, indicating adequate indispensable amino acid density rather than nutritional deficiency. The phytate:mineral analysis refined interpretation of the mineral data. Elevated phytate:Fe ratios across all species suggest constrained non-heme iron bioavailability despite relatively high iron concentrations in some accessions [10, 23, 28, 29]. In contrast, the comparatively low phytate:Ca ratio observed for *C. cajan* indicates a more favorable predicted calcium profile. These findings also support the potential value of processing strategies such as soaking, germination and fermentation to reduce phytate content and improve mineral accessibility [10, 30, 31]. Principal component analysis further demonstrated that these legumes represent distinct nutritional matrices rather than a homogeneous group. *Lablab purpureus* and *Vigna unguiculata* were characterized by protein-rich, antioxidant-associated profiles with high lysine density and favorable amino acid scores. Although antioxidant assays such as DPPH, ABTS and FRAP cannot demonstrate direct cellular pathway modulation, their association with phenolic content is consistent with previously reported roles of dietary polyphenols in redox buffering and inflammatory regulation through Nrf2/ARE- and NF-κB-related pathways [25, 32, 33]. Conversely, *C. cajan* occupied a distinct fiber–calcium niche with a comparatively favorable phytate:calcium ratio, supporting its potential use in formulations targeting dietary fiber enrichment and mineral diversification. Dietary fiber has been associated with microbial fermentation, generation of short-chain fatty acids, epithelial energy metabolism, intestinal barrier integrity and immunometabolic signaling [8, 34, 35]. Furthermore, because all evaluated species exceeded the FAO/WHO indispensable amino acid reference pattern, they may contribute to protein adequacy in cereal-based or animal-protein-limited diets [9]. Nevertheless, interpretation of mineral quality should remain cautious because elevated phytate ratios predict reduced non-heme iron bioavailability. Therefore, compared with USDA FoodData Central data for commonly consumed legumes, these Ecuadorian accessions should be viewed not as a single superior nutritional profile but as complementary matrices for targeted ingredient selection, dietary diversification and sustainable plant-based nutrition [36].

Finally, the conceptual model presented in Fig. 3 integrates the experimentally measured components with plausible physiological domains, linking phenolic-associated antioxidant responses to redox-inflammatory signaling, dietary fiber to microbiota-derived metabolites and gut barrier physiology, indispensable amino acids to protein adequacy, and phytate–mineral interactions to predicted mineral bioavailability [11, 37].

Conclusion

Overall, these findings indicate that Ecuadorian legumes constitute differentiated plant matrices whose translational relevance is supported by complementary nutritional mechanisms: phenolic compounds associated with antioxidant responses and redox-inflammatory regulation; dietary fiber linked to microbial fermentation and gut barrier physiology; high compositional protein quality supported by indispensable amino acid adequacy and cereal-legume complementation; and phytate ratios predicting differential constraints on mineral bioavailability, particularly that of non-heme iron.

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Disclosure Statement

The authors declare no conflicts of interest.

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