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Black Chickpea Landraces as a Sustainable Protein Source: Physicochemical, Nutritional, and Technological Properties

Marco Torre[1,2,3] | Olimpia Pitirollo[4] | Roberto Laganà Vinci[5] | Antonella Cavazza[4] | Francesco Cacciola[6] | Jens J. Sloth[7] | Charlotte Jacobsen[8] | Federico Casanova[3] | Antonella Verzera[1] | Fabrizio Cincotta[1]

[1]Department of Veterinary Sciences, University of Messina, Messina, Italy | [2]Department of Agricultural, Forest and Food Sciences – DISAFA, University of Turin, Torino, Italy | [3]Food Production Engineering, National Food Institute, Technical University of Denmark, Kgs. Lyngby, Denmark | [4]Department of Chemistry, Life Sciences and Environmental Sustainability, University of Parma, Parma, Italy | [5]Chromaleont s.r.l., c/o Department of Chemical, Biological, Pharmaceutical and Environmental Sciences, University of Messina, Messina, Italy | [6]Messina Institute of Technology c/o Department of Chemical, Biological, Pharmaceutical and Environmental Sciences, University of Messina, Messina, Italy | [7]Research Group for Analytical Food Chemistry, National Food Institute, Technical University of Denmark, Kgs. Lyngby, Denmark | [8]Research Group for Bioactives–Analysis and Application, National Food Institute, Technical University of Denmark, Kgs. Lyngby, Denmark

Correspondence: Fabrizio Cincotta (fabrizio.cincotta@unime.it)

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ABSTRACT

Neglected legume landraces represent valuable genetic resources for sustainable food systems, yet their compositional and technological properties remain poorly explored. This study comprehensively characterized the flours obtained from two Sicilian black chickpeas (*Cicer arietinum* L.) landraces, Rough Black Chickpeas (RBC) and Smooth Black Chickpeas (SBC), focusing on their chemical composition, nutritional profile, and technological properties using standardized analytical methods. Both flours showed a balanced macronutrient profile with significant genotype-dependent variations. SBC exhibited higher contents of protein (20.17 vs. 19.32 g/100 g), dietary fiber (7.14 vs. 6.23 g/100 g), and fat (4.66 vs. 4.36 g/100 g), as well as a higher total mineral content (18.65 vs. 17.84 g/kg) compared to RBC. Conversely, RBC showed higher total carbohydrates (59.34 vs. 57.29 g/100 g) and significantly higher levels of soluble sugars, including fructose (18.37 vs. 12.90 mg/100 g), galactose (17.43 vs. 7.76 mg/100 g), sucrose (85.39 vs. 56.40 mg/100 g), and stachyose (859.08 vs. 574.47 mg/100 g). Both cultivars met the FAO/WHO total essential amino acids requirements (SBC: 613.09; RBC: 649.12 mg/g protein), with methionine as the limiting amino acid (4.26–4.19 mg/g of protein). Phenolic profiling revealed shikimic acid, hydroxybenzoic and cinnamic derivatives, and catechin. Marked differences emerged in technological properties: RBC exhibited higher water absorption, swelling capacity, and emulsion stability, whereas SBC showed a more moderate hydration behavior. Overall, the results demonstrate that technological properties are strongly dependent on compositional and structural factors. These findings support the valorization of black chickpea landraces as sustainable and functional ingredients for innovative legume-based foods, contributing to biodiversity preservation and dietary diversification.

1 | Introduction

In recent years, legumes have gained increasing attention as central pillars of sustainable food systems due to their high nutritional value and low environmental impact (Yanni et al. 2023; Vilakazi et al. 2025). Their cultivation requires limited inputs, contributes to soil fertility through biological nitrogen fixation, and is associated with reduced greenhouse gas emissions compared to animal-based protein sources (FAO 2016). Moreover, legumes represent an important source

of plant-based proteins, dietary fiber, vitamins, minerals, and bioactive compounds, supporting both human health and global food security (Grdeń and Jakubczyk 2023; Lisciani et al. 2024).

Among grain legumes, chickpeas (*Cicer arietinum* L.) are one of the most widely cultivated and consumed pulses worldwide. They are characterized by a favorable nutritional profile, being rich in proteins, complex carbohydrates, dietary fiber, and essential micronutrients such as iron, magnesium, phosphorus, and folate. The consumption of chickpeas has been associated with several health benefits, including improved glycemic control and cardiovascular health, reinforcing its relevance in sustainable and health-oriented dietary patterns (Begum et al. 2023; Nam et al. 2023; Kumar et al. 2025). Chickpeas are generally classified into two major market types: "kabuli" and "desi" (Nezami et al. 2023; Xiao et al. 2023). Although kabuli chickpeas dominate global markets, desi types, characterized by smaller seeds and thicker, darker seed coats, have only recently attracted increasing interest due to their distinct compositional traits. In particular, pigmented chickpeas, such as black varieties, are known to contain higher levels of phenolic compounds, which contribute to their antioxidant capacity and potential functional properties (Macar et al. 2017; Kumar et al. 2025).

Despite this growing interest, most studies have focused on widely cultivated commercial varieties, whereas traditional and locally adapted chickpea landraces remain poorly characterized. In Mediterranean regions such as southern Italy, and especially in Sicily, chickpeas cultivation has deep historical roots and is supported by favorable pedoclimatic conditions. Local landraces are often grown under low-input and rainfed systems, making them well adapted to marginal environments and particularly relevant in the context of sustainable agriculture (Scordia et al. 2024). However, these genetic resources are still underutilized, and their potential for food applications remains largely unexplored.

Simultaneously, the development of legume-based ingredients has gained momentum in recent years, particularly for application in bakery products, pasta, snacks, and plant-based alternatives, driven by increasing consumer demand for sustainable protein sources (Foschia et al. 2017; Schmidt and Oliveira 2023; Webb et al. 2023; Huamaní-Perales et al. 2024). In this context, technological properties such as water absorption, emulsification, and gelation behavior play a crucial role in determining the performance of legume flours in food systems. These properties are strongly influenced by the chemical composition and structural characteristics of the raw material and are essential for predicting processing behavior and final product quality (Godschalk-Broers et al. 2022; Flory et al. 2023; Dinali et al. 2024; Perea-Escobar et al. 2025).

However, information on the technological and chemical–physical properties of flours derived from black chickpeas remains limited. In particular, there is a lack of studies focusing on traditional Mediterranean landraces, which may exhibit unique compositional traits compared to conventional cultivars. A better understanding of these properties is essential to support their valorization as ingredients and to promote their integration into modern food systems.

Therefore, this study aimed to comprehensively evaluate the chemical composition, including carbohydrate profile, mineral content, phenolic compounds, and technological properties of flours obtained from two neglected Sicilian black chickpea landraces.

By providing an in-depth characterization of these landraces, this work seeks to contribute to their valorization as sustainable and nutritionally valuable ingredients for the development of innovative legume-based food products.

2 | Materials and Methods

2.1 | Sampling and Milling Process

Two landraces of desi black chickpeas (*C. arietinum* L.), namely Rough Black Chickpeas (RBC) and Smooth Black Chickpeas (SBC) (Figure 1), were collected in 2025 from a custodian farmer in the province of Caltagirone (Sicily, Italy).

The grains were first cleaned to remove impurities and foreign materials and then milled using a laboratory disc mill DLFU (Bühler Group, Uzwil, Switzerland). The resulting flours were vacuum-packed and stored at 4°C until further analysis.

2.2 | Proximal Composition

Moisture, ash, total dietary fiber, protein, and fat contents were determined according to AOAC International methods 942.05, 978.10, 2001.11, 920.39, and 934.01, respectively (AOAC INTERNATIONAL 2023). Carbohydrate content was calculated by difference.

2.3 | Amino Acid Determination

Amino acid composition was determined based on the method described by Ghelichi et al. (2025). Approximately 30 mg of each sample was hydrolyzed with 6 M HCl at 110°C for 18 h. The hydrolysates were then filtered through 0.22 μm cellulose acetate spray filters. Then, the pH was adjusted by adding 0.2 M KOH, followed by ammonium acetate buffer (100 mM; pH 3.1 adjusted with formic acid). Amino acid analysis was performed by LC–MS (Agilent 1260 Infinity II Series, LC/MSD Trap, Agilent Technologies, Santa Clara, CA, USA) equipped with a BioZen 2.6 μm Glycan, 100 × 2.1 mm (00D-4773-AN) column (Phenomenex, Torrance, CA, USA) connected to a Quadrupole 6120 MS (Agilent Technologies) with an ESI ion source. The settings were: flow rate 0.5 mL/min; column temperature 40°C, injection volume 1 μL; run time 16 min. A gradient mix of two mobile phases, A (10 mM ammonium formate in acetonitrile) and B (10 mM ammonium formate in MilliQ water), was used as follows: 0–2 min 0%–5% phase B, 2–7 min 5%–20% phase B, 7–8 min 20%–80% phase B, 12.1 min 0% phase B, and 12.1–16 min 0% phase B. Standard curves were created by running a mix of amino acid standards containing 17 amino acids (excluding glutamine, tryptophan, and asparagine) at five different concentrations. The amino acids were quantified using MassHunter Quantitative Analysis version 7.0 software (Agilent

FIGURE 1 | Representative image of the two black chickpea (*Cicer arietinum* L.) landraces.

Technologies, Santa Clara, CA, USA). Glutamine, asparagine, tryptophan, and cysteine were not determined due to their degradation under acidic hydrolysis conditions. Measurements were carried out in triplicate.

2.4 | Carbohydrates Determination

2.4.1 | Extraction Procedure

The extraction of carbohydrates was performed in accordance with the procedure reported by Pitirollo et al. (2023). Briefly, 0.4 g of flour was mixed with 1 mL of methanol and subjected to ultrasound-assisted extraction (UAE) for 1 min. Subsequently, 20 mL of Milli-Q water was added, and UAE extraction continued for 5 min. Samples were then centrifuged (6000 rpm, 15 min, 4°C), and the supernatant was collected. The residue was re-extracted under the same conditions, and supernatants were combined (final volume: 41 mL). Extracts were then filtered through Stericup 0.45 μm nylon filters and purified using a pre-packed Dionex On-Guard II P cartridge before analysis.

2.4.2 | HPAEC-PAD Analysis

Carbohydrate analyses were performed using a Dionex ICS6000 SP/Dionex ICS6000 DC liquid chromatograph (Thermofisher Scientific) equipped with an AS50 Dionex autosampler with a 25 μL loop. An ED50A model pulsed amperometric detector (PAD) with an Ag/AgCl reference electrode and a gold working electrode was used. The mobile phase was prepared by a suitable dilution of water (Eluent A), 600 mM NaOH (Eluent B), and 500 mM sodium acetate (Eluent C). Before usage, all eluents were degassed with helium and, during chromatographic runs, were always kept under helium to avoid carbonate ions formation. The CHROMELEON software was used for recording chromatographic data. Chromatographic columns selected were a CarboPac PA100 (4 × 250 mm) column connected to the corresponding guard column CarboPac PA100 (4 × 50 mm) for oligosaccharides separation, and a CarboPac PA1 (4 × 250 mm) column connected to the corresponding guard column CarboPac PA1 (4 × 50 mm) for simple sugar separation.

Qualitative and quantitative analysis of galactooligosaccharides (GOS) was performed using a CarboPac PA100 column, and a gradient method was used at a flow rate of 0.5 mL/min. The standard raffinose and stachyose were analyzed in triplicate in the range of 0.5–25.0 μg/mL at seven concentration levels for a total run time of 45 min. The qualitative and quantitative analysis of simple sugars, polyols, mono-, and di-saccharides was carried out using a CarboPac PA1 column. An isocratic method was used for the separation, followed by washing and re-equilibration of the column for a total run time of 80 min at a flow rate of 1.0 mL/min. All standards (xilitol, sorbitol, mannitol, galactose, glucose, fructose, sucrose, lactose) were analyzed in triplicate in the range of 0.25–50.0 μg/mL. All samples were analyzed in triplicate.

2.5 | Polyphenol Determination

2.5.1 | Extraction Procedure

For the polyphenol determination, 1 g of flour was weighed in a plastic centrifuge tube with a screw cap, and 10 mL of extraction solvent (MeOH: H_2O, 80:20 v/v) was added. Afterwards, the mixture was stirred using an ultrasonic bath for 10 s, and centrifuged at 5000 rpm for 20 min. The supernatant was collected in a new 50 mL centrifuge tube. The solid residue was washed twice with 7.5 mL of extraction solvent and centrifuged again until a final volume of 25 mL supernatant was collected. The solution obtained was immediately stored in the freezer overnight at −24°C to precipitate protein or lipidic residues that

might interfere during HPLC-MS analysis. After this step, the methanolic solution was separated by residue, and the methanol was evaporated using a Rotary Evaporator.

2.5.2 | Total Phenolic Content

Total phenolic content was determined using the Folin–Ciocalteu method. Briefly, 100 μL of extract was mixed with 750 μL of Folin–Ciocalteu reagent (diluted 1:10) and 750 μL of sodium carbonate solution (6%, w/v). The mixture was incubated at room temperature in the dark for 60 min, and the absorbance was measured at 725 nm using a UV–Vis spectrophotometer (Shimadzu UV mini 1240, Duisburg, Germany). Gallic acid was used as the standard (0–200 mg/L), and results were expressed as mg gallic acid equivalents (GAE) per g of sample dry weight (dw).

2.5.3 | HPLC Analysis

Chromatographic analysis was accomplished using a Shimadzu HPLC system (Kyoto, Japan) equipped with a CBM-20A controller, two LC-20 AD dual-plunger parallel-flow pumps, a DGU20A5R degasser, a CTO-20 AC column oven, a SIL-30 AC autosampler, an SPD-M20A photodiode array detector, and an LCMS-2020 single quadrupole mass spectrometer, with the employment of ESI source operated in negative ionization mode (Laganà Vinci et al. 2024). Chromatographic separations were carried out on an Ascentis Express RP C18 column (150 × 2.1 mm; 2.7 μm) (Merck Life Science, Merck KGaA, Darmstadt, Germany). The employed mobile phase comprised two solvents: water (solvent A) and acetonitrile (solvent B), both acidified with 0.10% of formic acid (*v/v*). The flow rate was set at 1 mL/min, under gradient elution 0–5 min, 0%–5% B, 10 min, 15% B, 20 min, 30% B, 60 min, 50% B, 70 min, 100% B, 75 min, 100% B. The injection volume was 5 μL. Diode array detection (DAD) was applied in the range of 200–400 nm and monitored at a wavelength of 330 nm (sampling frequency: 40 Hz, time constant: 0.080 s). MS conditions were as follows: scan range and the scan speed were set at a mass-to-charge ratio (m/z) 100–1600 and 7500 amu/s, respectively; Event time: 0.3 s, nebulizing gas (N_2) flow rate: 1.5 L/min, drying gas (N_2) flow rate: 15 L/min, interface temperature: 350°C, heat block temperature: 300°C, desolvation line temperature: 300°C, desolvation line voltage: 1 V, interface voltage: −4.5 kV. Calibration curves of two polyphenolic standards (gallic acid and catechin) were employed for the quantification of the polyphenolic content in sample extracts (gallic acid, $y = 12{,}999x + 54{,}347$, $R^2 = 0.9996$; LOD = 0.041, LOQ = 0.125; catechin, $y = 2642.6x + 2524.8$, $R_2 = 0.9999$, LOD = 0.149, LOQ = 0.452). Each analysis was performed in 6 repetitions. Data acquisition was performed by Shimadzu LabSolution software ver. 5.99.

2.6 | Mineral Composition

The mineral composition was assessed according to Dadi et al. 2025, with minor adaptations. Macroelements (Ca, K, Na, P, S) were quantified by inductively coupled plasma optical emission spectrometry (Agilent 5800 ICP-OES), whereas microelements (Al, Cr, Fe, Mn, Ni, Cu, Zn, Se, Sr., Sn, Ba, As, Cd, Hg and Pb) were determined using inductively coupled plasma mass spectrometry ICP-MS (Thermo Fischer Scientific iCAPTQ ICP-MS, Bremen, Germany). Before instrumental analysis, samples were microwave-assisted digested with concentrated nitric acid using a Multiwave 7000 system (Anton Paar, Graz, Austria). The resulting digests were subsequently diluted with MilliQ ultrapure water. All measurements were performed in duplicate. Quantification relied on external calibration combined with internal standards, using rhodium (Rh) and bismuth (Bi) for ICP-MS analyses and yttrium (Y) for ICP-OES. Calibration standards were prepared from certified stock solutions supplied by SPS Science. Quality control of the analytical process was ensured through the inclusion of certified reference materials, specifically NIST 1572 (citrus leaves) and DORM-5 (fish protein).

2.7 | Color Profile

The color parameters (L^*, a^*, b^*) were determined by using the reflection method in the CIELAB* system with a CM-2500d colorimeter (Konica Minolta, Osaka, Japan) previously calibrated using the required calibration plate. Measurements were performed in triplicate. Color-derived parameters, including chroma (C*), hue angle (H°), yellowness index (YI), and whiteness index (WI), were calculated using the equations reported by Adebo (2025) and Adeyanju et al. (2025), whereas the browning index was expressed using that reported by Emerald et al. (2020).

2.8 | Technological Properties

2.8.1 | Particle Size Distribution

Particle size distribution of chickpea flour was determined using the ANSI/ASAE S319.4 sieve method (ASABE 2008). Approximately 100 g of chickpea flour was accurately weighed and placed into the topmost sieve of a stack of stainless-steel sieves arranged in descending order of aperture size (2000, 1000, 500, 250, and 125 μm), with a collecting pan positioned at the bottom of the stack. The sieve stack was mounted on a mechanical shaker (Retsch AS 200 control) and subjected to continuous shaking for 10 min to ensure effective separation of particles according to their size. After the sieving process, the material retained on each sieve and in the collecting, pan was carefully recovered and weighed. The percentage of material retained on each sieve was calculated relative to the initial sample mass. The particle size distribution was then expressed by plotting the percentage of retention against the corresponding sieve aperture size. All analyses were carried out in triplicate.

2.8.2 | Bulk Density (BD)

Bulk density (BD) was determined by transferring flour samples into a pre-weighed 10 mL graduated cylinder. The cylinder was filled to the 10 mL mark and gently tapped on the laboratory bench until a constant volume was obtained (Du et al. 2014). Bulk density was expressed as the mass of flour per unit volume (g/mL). All measurements were performed in triplicate.

2.8.3 | Water Absorption Capacity (WAC)

Water absorption capacity (WAC) was determined by dispersing 3.0 g of flour in 25 mL of distilled water and transferring the mixture into pre-weighed centrifuge tubes (50 mL). The suspensions were mixed at 5 min intervals for 30 min and then centrifuged at 3000 ×*g* for 30 min. After centrifugation, the supernatant was discarded, and the residues were allowed to drain at 50°C for 25 min to remove excess moisture. The tubes were then weighed. Water absorption capacity was expressed as g of water retained per g of dry sample (Du et al. 2014).

2.8.4 | Oil Absorption Capacity (OAC)

Oil absorption capacity (OAC) was determined by mixing 2.5 g of flour with 30 mL of peanut oil in pre-weighed centrifuge tubes. The mixtures were stirred for 1 min, allowed to stand for 30 min, and then centrifuged at 3000 ×*g* for 30 min. After centrifugation, the unbound oil was removed, and the tubes were inverted for 25 min to drain residual oil. The tubes were then weighed, and oil absorption capacity was expressed as g of oil retained per g of dry sample (Du et al. 2014).

2.8.5 | Water Solubility Index (WSI) and Water Absorption Index (WAI)

A legume flour sample (2.5 g) was dispersed in 30 mL of distilled water and cooked in a water bath at 70°C for 30 min. The cooked paste was then cooled to room temperature, transferred into pre-weighed centrifuge tubes, and centrifuged at 3000 ×*g* for 20 min. The supernatant was decanted into a pre-weighed evaporating dish, and its solid content was determined by drying overnight at 105°C. The sediment was also weighed. Water absorption index (WAI) and water solubility index (WSI) were calculated using the equations reported by Du et al. (2014).

2.8.6 | Emulsifying Properties

Emulsifying properties were determined according to the method reported by Du et al. (2014) with some modifications. Emulsion activity (EA) was assessed by dispersing 3.5 g of flour in 50 mL of distilled water and homogenizing the mixture at 10,000 rpm for 30 s using an Ultra-Turrax (T18, IKA Corporation, Germany). Subsequently, 25 mL of peanut oil was added and homogenized for 30 s, followed by a second addition of 25 mL of oil and a final homogenization for 90 s. The resulting emulsion was divided equally into two 50 mL centrifuge tubes and centrifuged at 1100 ×g for 5 min. Emulsifying activity was expressed as the ratio between the volume of the emulsified layer and the initial emulsion volume before centrifugation, multiplied by 100.

Emulsion stability (ES) was evaluated using the same emulsions. The samples were heated at 85°C for 15 min, cooled to room temperature, and centrifuged again at 1100 ×g for 5 min. Stability was expressed as the percentage of emulsifying activity retained after the heat treatment.

2.8.7 | Least Gelation Concentration (LGC)

The least gelation concentration (LGC) was determined according to the method of Kaur and Singh (2005). Test tubes containing suspensions of chickpea flour at concentrations of 2%, 4%, 6%, 8%, 10%, 12%, 14%, 16%, 18%, and 20% (w/v) in 5 mL of distilled water were heated in a boiling water bath for 1 h, followed by rapid cooling under cold running water. The tubes were then cooled at 4°C for 2 h. The LGC was defined as the lowest concentration at which the sample did not flow or slide upon inverting the test tube.

2.9 | Statistical Analysis

Statistical analyses were performed using JMP Pro version 17.0.0 (SAS Institute Inc., Cary, North Carolina, USA). Differences between the two groups were evaluated using independent samples *t*-tests. Before analysis, data were assessed for normality and homogeneity of variances using the Shapiro–Wilk and Levene tests, respectively. When the assumption of equal variances was not met, Welch's *t*-test was applied. Data were expressed as mean ± standard deviation (SD) of three replicates. Statistical significance was set at $p < 0.05$.

Chemical–physical and technological data were subjected to principal component analysis (PCA) using XLStat software, version 2024.1 (Addinsoft, New York, New York, USA) to identify variability and relationships among variables. Before analysis, the dataset was normalized to remove scale effects and ensure comparability across parameters.

3 | Results and Discussion

3.1 | Proximate Composition

The proximate composition of SBC and RBC flours (Table 1) showed statistically significant but moderate differences for some macronutrients. SBC exhibited higher ($p < 0.05$) fat (4.66 g/100 g vs. 4.36 g/100 g), protein (20.17 g/100 g vs. 19.32 g/100 g), and dietary fiber contents (7.14 g/100 g vs. 6.23 g/100 g), whereas a higher carbohydrate content (59.34 g/100 g vs. 57.29 g/100 g) characterized RBC flour.

TABLE 1 | Proximate composition (g/100 g) of whole Smooth Black Chickpea (SBC) and Rough Black Chickpea (RBC) flours.

	SBC	RBC
Fat	4.66 ± 0.10^{a}	4.36 ± 0.13^{b}
Carbohydrates	57.29 ± 0.24^{b}	59.34 ± 0.31^{a}
Fibers	7.14 ± 0.01^{a}	6.23 ± 0.02^{b}
Proteins	20.17 ± 0.02^{a}	19.32 ± 0.12^{b}
Hash	2.86 ± 0.01^{a}	2.84 ± 0.02^{a}
Moisture	7.88 ± 0.01^{a}	7.91 ± 0.05^{a}

Note: Different superscript letters in the same row indicate statistically significant differences at $p < 0.05$.

TABLE 2 | Amino acids (AAs) content of Smooth Black Chickpea (SBC) and Rough Black Chickpea (RBC) flours.

	SBC	RBC	SBC	RBC	Adult daily requirements (mg/g proteins)*
	mg/g of flour		mg/g of proteins		
Essential AAs (EAAs)					
Histidine	nd	nd	nd	nd	15
Leucine	27.94 ± 0.92^{b}	29.79 ± 2.83^{a}	138.52 ± 4.56^{b}	154.19 ± 4.76^{a}	59
Isoleucine	10.25 ± 0.14^{a}	9.62 ± 0.36^{b}	50.82 ± 0.69^{a}	49.79 ± 1.86^{b}	30
Lysine	9.63 ± 0.22^{a}	8.98 ± 1.38^{a}	47.74 ± 1.09^{a}	46.48 ± 7.14^{a}	45
Methionine	0.86 ± 0.24^{a}	0.81 ± 0.11^{a}	4.26 ± 1.09^{a}	4.19 ± 0.57^{a}	22 (Met + Cys)
Phenylalanine	55.85 ± 0.28^{b}	57.88 ± 5.19^{a}	276.90 ± 1.39^{b}	299.59 ± 26.86^{a}	38 (Phe + Tyr)
Tyrosine	4.44 ± 0.27^{a}	4.33 ± 0.30^{a}	22.01 ± 1.34^{a}	22.41 ± 1.55^{a}	
Threonine	5.56 ± 0.35^{a}	5.35 ± 0.06^{a}	27.57 ± 1.74^{a}	27.69 ± 0.31^{a}	23
Valine	9.13 ± 0.48^{a}	8.66 ± 0.56^{a}	45.27 ± 2.38^{a}	44.82 ± 2.90^{a}	39
$\sum EAAs$	**123.66 ± 1.22**	**125.41 ± 6.11**	**613.09 ± 6.05**	**649.12 ± 31.63**	**277**
Non-essential AAs (NEAAs)					
Alanine	7.59 ± 0.06^{a}	7.45 ± 0.23^{b}	37.63 ± 0.30^{a}	38.56 ± 1.19^{b}	
Arginine	19.23 ± 0.54^{a}	19.60 ± 0.86^{a}	95.34 ± 2.68^{b}	101.45 ± 4.45^{a}	
Aspartic acid	0.49 ± 0.23^{a}	0.42 ± 0.29^{a}	2.43 ± 2.68^{a}	2.17 ± 1.50^{a}	
Glutamic acid	nd	nd	nd	nd	
Glycine	7.25 ± 0.41^{a}	7.28 ± 0.33^{a}	35.94 ± 2.03^{a}	37.68 ± 1.71^{a}	
Proline	9.34 ± 0.22^{a}	8.88 ± 0.26^{b}	46.31 ± 1.09^{a}	45.96 ± 1.35^{b}	
Serine	10.17 ± 0.30^{a}	9.80 ± 0.17^{a}	50.42 ± 1.49^{a}	50.72 ± 0.88^{a}	
$\sum NEAAs$	**54.08 ± 0.81**	**53.43 ± 1.04**	**268.12 ± 4.02**	**276.55 ± 5.38**	
$\sum AAs$	**177.74 ± 1.46**	**178.84 ± 6.20**	**881.21 ± 7.24**	**925.67 ± 32.09**	

Note: Different superscript letters in the same row indicate statistically significant differences at $p < 0.05$. *Adult requirements are those reported by WHO, FAO, UNU (2007).

These differences are consistent with the variability reported for desi-type chickpeas (Kumar et al. 2020) and black chickpea (Shahid et al. 2024). Although quantitatively limited, these differences are relevant for the technological properties. The higher protein and fiber content of SBC may contribute to enhanced structural properties in food matrices. In contrast, the higher carbohydrate content in RBC is consistent with its superior hydration and swelling behavior observed in the subsequent analyses. This suggests that even small compositional variations can translate into meaningful technological differences, highlighting the importance of genotype selection for targeted food applications.

3.2 | Amino Acid Composition

Table 2 reports the amino acid (AA) composition of Smooth Black Chickpea (SBC) and Rough Black Chickpea (RBC) flours, calculated both on a flour weight basis (mg/g of flour) and as protein density (mg/g of proteins). Both chickpea cultivars exhibited a robust and well-balanced AA profile, though specific statistically significant differences ($p < 0.05$) were observed between the two samples.

The amino acid profiles of SBC and RBC flours were comparable and aligned with those typically reported for chickpea proteins, with leucine and phenylalanine as the predominant essential amino acids (EAAs) (Begum et al. 2023; Kumar et al. 2025). RBC flour showed slightly higher content of leucine (29.79 mg/g) and phenylalanine (57.88 mg/g) compared to SBC, whereas SBC showed a significantly higher content of isoleucine (10.25 mg/g) than RBC (9.62 mg/g). Conversely, no significant variations were detected between the two raw flours for lysine, methionine, tyrosine, threonine, and valine.

Within the non-essential amino acids (NEAAs), arginine, serine, proline, and alanine were among the most abundant, consistent with previously reported amino acid patterns in chickpea (Begum et al. 2023). SBC flour was characterized by significantly higher content of alanine (7.59 mg/g) and proline (9.34 mg/g). On the other hand, RBC flour exhibited a significantly higher concentration of arginine (19.60 mg/g) compared

TABLE 3 | Qualitative and quantitative (mg/100 g) sugar composition of whole Smooth Black Chickpea (SBC) and Rough Black Chickpea (RBC) flours.

Sugar	LOD (mg/L)	LOQ (mg/L)	SBC	RBC
Xylitol	0.0057	0.0189	8.55 ± 0.59^{a}	6.24 ± 0.36^{b}
Sorbitol	0.0146	0.0487	7.50 ± 0.27^{a}	7.67 ± 0.82^{a}
Mannitol	0.0308	0.1028	6.51 ± 0.25^{a}	2.62 ± 0.42^{b}
Galactose	0.0160	0.0550	7.76 ± 0.65^{b}	17.43 ± 5.64^{a}
Glucose	0.0059	0.0198	8.50 ± 0.32^{b}	14.55 ± 3.16^{a}
Fructose	0.0258	0.0862	12.90 ± 1.85^{b}	18.37 ± 2.68^{a}
Sucrose	0.0283	0.0943	56.4 ± 6.20^{b}	85.39 ± 17.04^{a}
Raffinose	0.1832	0.6108	686.72 ± 57.79^{b}	721.71 ± 62.58^{a}
Stachyose	0.1365	0.4549	574.47 ± 52.00^{b}	859.08 ± 58.97^{a}

Note: Different superscript letters in the same row indicate statistically significant differences at $p < 0.05$.

to SBC (19.23 mg/g). The total amino acid content of the flours remained statistically comparable, yielding 177.74 mg/g for SBC and 178.84 mg/g for RBC.

From a nutritional perspective, both black chickpea varieties demonstrated exceptional potential, vastly exceeding the total AA adult daily requirement of 277 mg/g protein established by the WHO/FAO/UNU (2007). Legumes are widely recognized as excellent sources of lysine, an amino acid typically limiting in cereal grains; in this study, both SBC (47.74 mg/g protein) and RBC (46.48 mg/g protein) successfully satisfied the reference requirement of 45 mg/g protein. Hydrophobic and aromatic AAs were particularly abundant. Leucine concentrations (138.52 mg/g protein for SBC; 154.19 mg/g protein for RBC) were more than double the reference value of 59 mg/g protein. Similarly, the combined values of phenylalanine and tyrosine far exceeded the recommended target of 38 mg/g protein. Nevertheless, typical legume nutritional constraints were observed. Methionine content (4.26 mg/g protein for SBC and 4.19 mg/g protein for RBC) fell short of the combined sulfur AA requirement (Met + Cys = 22 mg/g protein), confirming that sulfur-containing AAs remain the primary limiting factors, as widely reported in literature (Jha et al. 2024). Additionally, histidine and glutamic acid were not detected in either cultivar.

The findings confirm black chickpea as a promising candidate for dietary diversification and food innovation in line with current interest in sustainable vegetal protein systems.

3.3 | Sugar Profile

The carbohydrate profile of SBC and RBC flours (Table 3) showed clear quantitative significant differences across mono-, di-, and oligosaccharides content. Overall, RBC showed a higher concentration of most sugars, particularly galactose, glucose, fructose, sucrose, raffinose, and stachyose, whereas SBC had a relatively lower amount, except for some polyols.

Among sugar alcohols, xylitol and mannitol were present at higher concentrations in SBC (5.55 and 6.51 mg/100 g, respectively), whereas the amount of sorbitol was comparable between the two flours. Although present at low concentrations, these compounds may reflect genotype-dependent metabolic responses associated with stress tolerance mechanisms (Jenisha et al. 2026).

As regards monosaccharides, RBC showed higher content of galactose (17.43 vs. 7.76 mg/100 g), glucose (14.55 vs. 8.50 mg/100 g), and fructose (18.37 vs. 12.90 mg/100 g) compared to SBC. The observed values are consistent with previously reported variability in monosaccharides across chickpea landraces, largely influenced by seed coat type and genetic background. In fact, chickpea monosaccharide content can vary widely, particularly in desi-type chickpeas, which tend to have higher reducing sugars and more complex carbohydrate profiles (Kumar et al. 2025). The highest monosaccharide content in RBC may also reflect its wrinkled morphology, typically associated with altered starch deposition and increased simple sugar accumulation (Daba et al. 2025).

As regards the disaccharides, sucrose was the predominant one and was significantly more abundant in RBC (85.39 mg/100 g) than in SBC (56.40 mg/100 g). These data agree with recent large-scale characterizations showing that sucrose concentration in chickpea varies considerably across genotypes (ranging broadly from ~3.6 to 54 mg/g), with Kabuli-types often accumulating higher sucrose (Elango et al. 2022). Sucrose also plays important roles in seed desiccation tolerance, carbon allocation, and germination vigor. Studies in chickpea have shown strong genetic regulation of sucrose-associated metabolic traits, mediated by candidate genes such as *UDP-glucose dehydrogenase* and *remorin proteins* (Elango et al. 2022).

Among oligosaccharides (Raffinose Family Oligosaccharides, RFOs), raffinose and stachyose were found in both flours, consistent with typical legume RFO profiles. RBC showed higher content of both raffinose (721.71 vs. 686.72 mg/100 g) and stachyose (859.08 vs. 574.47 mg/100 g) than SBC.

RFOs, known contributors to flatulence due to human indigestibility, also possess important physiological functions in plants

TABLE 4 | Mineral composition (mean ± SD, $n = 3$) of whole Smooth Black Chickpea (SBC) and Rough Black Chickpea (RBC) flours.

		LOQ	SBC	RBC	Daily reference consumption*
Macrominerals (g/kg)	**Ca**	0.024	1.59 ± 0.05^{a}	1.27 ± 0.04^{b}	800 mg
	K	0.109	11.02 ± 0.52^{a}	11.12 ± 0.27^{a}	2000 mg
	Na	0.003	0.08 ± 0.01^{a}	0.09 ± 0.001^{a}	
	P	0.004	3.76 ± 0.22^{a}	3.21 ± 0.09^{b}	700 mg
	S	0.004	2.05 ± 0.15^{a}	2.00 ± 0.02^{a}	
Microminerals (mg/kg)	**Al**	0.9	6.40 ± 0.03^{a}	4.46 ± 0.04^{b}	
	Cr	0.06	0.17 ± 0.01^{a}	0.05 ± 0.01^{b}	40 μg
	Fe	0.05	50.09 ± 0.07^{b}	53.27 ± 0.02^{a}	14 mg
	Mn	0.011	23.35 ± 0.03^{a}	20.45 ± 0.61^{b}	2 mg
	Ni	0.025	1.06 ± 0.24^{a}	0.480 ± 0.001^{b}	
	Cu	0.05	7.34 ± 0.03^{b}	8.74 ± 0.03^{a}	1 mg
	Zn	2.3	43.03 ± 0.16^{a}	43.01 ± 0.33^{a}	10 mg
	Se	0.05	0.06 ± 0.01	<LOQ	55 μg
	Sr	0.017	10.18 ± 0.59^{b}	21.82 ± 0.27^{a}	
	Sn	0.02	0.02 ± 0.01	<LOQ	
	Ba	0.05	3.33 ± 0.004^{a}	1.95 ± 0.07^{b}	
Heavy metals (mg/kg)	**As**	0.013	0.010 ± 0.001	<LOQ	
	Cd	0.0012	0.010 ± 0.001^{a}	0.010 ± 0.001^{a}	
	Hg	0.004	<LOQ	<LOQ	
	Pb	0.01	<LOQ	<LOQ	
Total minerals (g/kg)			$\mathbf{18.65 \pm 0.95^{a}}$	$\mathbf{17.84 \pm 0.42^{b}}$	

Note: Different superscript letters in the same row indicate statistically significant differences at $p < 0.05$; LOQ: Limit of quantification; Daily reference *Consumption based on Regulation (UE) N. 1169/2011 (European Commission 2011).

related to stress tolerance, seed longevity, and carbon storage. Their high abundance in chickpeas is well documented, and recent multi-genotype analyses confirm large natural variation in RFOs across germplasm (Elango et al. 2022). Moreover, expression studies show that genes involved in RFO biosynthesis, such as *galactinol synthase* and *raffinose synthase*, are tightly regulated under abiotic stress and hormonal signals (Jenisha et al. 2026). These regulatory mechanisms may explain the high concentration and the differences observed between SBC and RBC flours.

In addition to their metabolic functions in plants, these sugars have important nutritional implications. Chickpeas are recognized as a source of prebiotic carbohydrates, particularly RFOs, which contribute to beneficial gut microbiota such as *Bifidobacterium* (La-ongkham et al. 2025). The higher RFO content in RBC may thus confer enhanced prebiotic potential, although this must be balanced against possible gastrointestinal discomfort in sensitive consumers. Furthermore, chickpeas have been increasingly highlighted for their diverse carbohydrate fractions that influence postprandial glycemia, starch digestibility, and health-promoting properties (Kumar et al. 2025).

The monosaccharide and sucrose differences observed here could translate into distinct technological properties in flour applications, for example, affecting browning reactions, sweetness perception, and fermentation behavior.

3.4 | Mineral Composition

The mineral composition of SBC and RBC flours revealed statistically significant differences in macro- and micro-mineral contents (Table 4). The total mineral content was significantly higher in SBC (18.65 g/kg) compared to RBC (17.84 ± 0.42 g/kg), suggesting that the seed coat morphology or genetic factors may favor a higher overall accumulation of inorganic elements.

Among macrominerals, potassium was the most abundant in both flours (11.02–11.12 g/kg), followed by phosphorus and sulfur, whereas calcium and sodium occurred at lower

concentrations. These values fall within the ranges commonly reported for chickpeas, which are typically rich in K, P, Mg, and Fe (Kumar et al. 2025). SBC flour showed slightly higher Ca and P content. These variations are consistent with the influence of genotype on mineral uptake and distribution, as demonstrated by large-scale evaluations reporting substantial inter-genotypic variability in chickpea germplasm (Hacisalihoglu et al. 2025). From a nutritional perspective, considering a standard daily portion of 100 g of chickpea flour, both SBC and RBC would supply approximately 1.1 g of K, covering over 55% of the Daily Reference Consumption (2000 mg) established by Regulation (EU) No. 1169/2011. This high potassium intake, combined with low sodium levels (0.08–0.09 g/kg), yields a remarkably low Na/K ratio, which is highly desirable for dietary interventions aimed at managing hypertension and cardiovascular health. Moreover, 100 g of SBC flour satisfies 53.7% of the daily reference consumption for P and 20% for Ca, whereas RBC covers 45.8% (P) and 16% (Ca), by electing SBC as a superior source for bone-health-related minerals.

Regarding microminerals, SBC showed higher concentrations of Al, Cr, Mn, and Ni, whereas RBC contained more Sr (21.82 vs. 10.18 mg/kg). Both flours were characterized by comparable Fe and Zn levels, in agreement with the relatively stable concentrations reported across chickpea varieties (Brun et al. 2024). The Fe content (50.09 and 53.27 mg/kg) further supports the nutritional relevance of black chickpeas. Selenium was detected only in SBC (0.06 mg/kg), whereas it was below quantification limits in the RBC samples. This difference likely reflects genotype × environment interactions, as selenium accumulation in legumes is strongly influenced by soil and agronomic conditions (Salaria et al. 2025). Regarding nutritional value, consuming 100 g of flour completely fulfills the daily requirement of Mn (2 mg), providing 116.7% in SBC and 102.2% in RBC. Mn acts as an essential cofactor for several enzymes, including superoxide dismutase, playing a pivotal role in antioxidant defense. As regards Cu, a single serving meets 87.4% and 73.4% of the daily reference intake (1 mg) for RBC and SBC, respectively. Finally, both flours meet about 43% of the daily recommended intake of Zn. Conversely, RBC was significantly richer in Fe (53.27 mg/kg) than SBC (50.09 mg/kg), contributing up to 38% of the daily reference value (14 mg). This makes black chickpea flours an excellent plant-based strategy to counteract iron deficiency.

Heavy metals (As, Cd, Hg, Pb) were either undetectable or present at trace levels in both flours, well below international safety thresholds (European Commission 2023). This is consistent with previous studies classifying chickpeas as low-risk accumulators of heavy metals (Kumar et al. 2025).

Overall, the mineral profiles of SBC and RBC flours are consistent with desi-type chickpeas, with differences potentially associated with seed coat structure and polyphenol deposition (Brun et al. 2024). The total mineral content (18.65 and 17.84 g/kg, respectively) confirms black chickpeas as valuable sources of dietary minerals. This aligns with the broader classification of chickpeas as sustainable, protein-rich but also micronutrient-rich crops in line with recent advances in legume research, which emphasize the role of chickpeas in enhancing dietary mineral intake (Salaria et al. 2025).

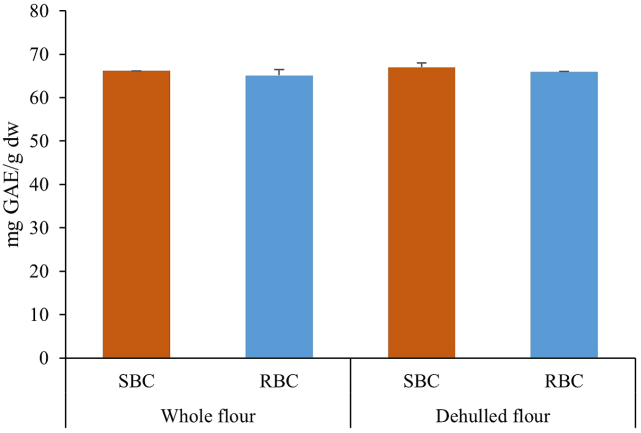

FIGURE 2 | Total Phenolic Content (TPC) of whole and dehulled Smooth Black Chickpea (SBC) and Rough Black Chickpea (RBC) flours.

3.5 | Total Phenolic Content and Polyphenol Profile

The total phenolic content (TPC) of the black chickpea flours showed no statistically significant variations among the different samples, with values ranging from 62.14 to 67.00 mg GAE/g dw (Figure 2). The limited differences observed between whole and dehulled flours suggest that cotyledons also contribute to the overall phenolic content, resulting in only a minor reduction after dehulling (Sreerama, Neelam, et al. 2010).

The phenolic profile of the SBC and RBC flour from whole and dehulled grains was further characterized by LC-PDA/ESI-MS in both negative and positive ionization modes. Compound identification was achieved by combining retention time (t_R), UV–Vis absorption maxima, pseudomolecular ions ($[M–H]^-$), and comparison with literature data (Table 5).

Overall, both flours exhibited a comparable qualitative phenolic pattern, characterized by the presence of shikimic acid and four phenolic acids, namely, hydroxybenzoic acid derivative, cinnamic acid glucoside, cinnamoyl-galloylglucose, and catechin. Among early-eluting compounds, shikimic acid (t_R 0.69 min, λ_{max} 224 nm, $[M–H]^-$ 173) was detected in all samples. Although not quantified, its occurrence is noteworthy because shikimic acid is a central intermediate in the biosynthesis of aromatic amino acids and downstream phenylpropanoids (El-Azaz and Maeda 2025). Its presence confirms the active phenylpropanoid metabolic pathway in black chickpea seeds and has been previously reported in legume matrices as a precursor of diverse phenolic compounds (Hernández-Ruiz et al. 2025). A hydroxybenzoic acid derivative (t_R 1.75 min, λ_{max} 263 nm, $[M–H]^-$ 289, 137) was also detected in both RBC and SBC, in whole and dehulled flours. The fragmentation pattern suggests the presence of a substituted benzoic acid structure. Hydroxybenzoic acids and their derivatives are common in pulses and are associated with antioxidants and antimicrobial properties; however, specific data on black chickpea flours are still limited, making this finding relevant for expanding the phytochemical knowledge of these underutilized landraces. In the mid-retention time region, cinnamic acid glucoside (t_R 8.05 min, λ_{max} 224,274 nm, $[M–H]^-$ 309) and cinnamoyl-galloylglucose (t_R 8.98 min, λ_{max} 277 nm, $[M–H]^-$ 461) were

TABLE 5 | Semi-quantification (mg/g dw) of phenolic compounds in MeOH:H_2O (80:20 v/v) extracts of whole and dehulled Smooth Black Chickpea (SBC) and Rough Black Chickpea (RBC) flours.

				Whole flour		Dehulled flour	
Compounds	**t_R**	**PDA**	**[M–H]$^-$**	**SBC**	**RBC**	**SBC**	**RBC**
Shikimic acid	0.69	224	173	x	x	x	x
Hydroxybenzoic acid derivative	1.75	263	289, 137	< LOQ	< LOQ	< LOQ	< LOQ
Cinnamic acid glucoside	8.05	224, 274	309	< LOQ	< LOQ	< LOQ	< LOQ
Cinnamoyl-galloylglucose	8.98	277	461	42.81 ± 0.250^b	47.48 ± 0.331^a	30.48 ± 0.223^d	37.71 ± 1.03^c
Catechin	11.53	278	289	3.39 ± 0.041^a	3.35 ± 0.011^a	2.94 ± 0.135^b	3.05 ± 0.09^b

Note: Different superscript letters in the same row indicate statistically significant differences at $p < 0.05$; x: detected but not quantified; LOQ: limit of quantification.

identified in all samples. The assignment was supported by UV spectra and mass fragmentation consistent with hydroxycinnamic acid derivatives previously described in legumes and seed coats (Zhong et al. 2019; Abdelaziz et al. 2020). These compounds belong to the class of conjugated phenolic acids, frequently localized in the outer layers of seeds and associated with defense mechanisms and antioxidant activity. Cinnamoyl-galloylglucose was semi-quantified and showed relatively high levels in both flours. In whole flour, SBC and RBC contained 42.81 ± 0.250 mg/g and 47.48 ± 0.331 mg/g extract, respectively. In dehulled flour, lower values were recorded (30.48 ± 0.223 mg/g for SBC and 37.71 ± 1.03 mg/g for RBC). The higher concentration in whole flour suggests that a substantial portion of this compound is associated with seed coat fractions. The slightly higher content observed in RBC compared to SBC indicates a genotype-dependent variability, in agreement with literature reporting significant differences in phenolic acid derivatives among chickpea cultivars and between desi and kabuli types. The late-eluting compound was represented by catechin (t_R 11.53 min, λ_{max} 278 nm, [M-H]$^-$ 289). In whole flour, catechin levels were 3.39 ± 0.041 mg/g extract in SBC and 3.35 ± 0.011 mg/g extract in RBC. In dehulled flour, slightly lower values were measured (2.94 ± 0.135 mg/g for SBC and 3.05 ± 0.09 mg/g for RBC). These results are in line with previous studies reporting catechin and other flavan-3-ols as major phenolic constituents of chickpeas, particularly in pigmented seed coats (Rocchetti et al. 2019). The relationship between seed coat pigmentation and total phenolic content in chickpeas has often been attributed to the accumulation of flavonoid compounds, including anthocyanins, flavan-3-ols, and other phenolic derivatives localized in the outer seed layers (Sreerama, Neelam, et al. 2010). Darker chickpea genotypes are frequently reported to exhibit higher phenolic levels than cream-colored kabuli types; however, the specific compounds responsible for these differences vary depending on genotype and extraction methodology (Segev et al. 2010). In some pigmented legumes, anthocyanins contribute substantially to seed coat coloration, whereas in chickpeas, darker pigmentation has also been associated with elevated levels of condensed tannins, catechin derivatives, and hydroxycinnamic acid conjugates rather than anthocyanins alone (Sreerama, Sashikala, et al. 2010). In the present study, no anthocyanins or isoflavones were detected under the adopted analytical conditions. Instead, the phenolic profile was mainly characterized by phenolic acid derivatives, particularly cinnamoyl-galloylglucose, together with catechin. This suggests that the antioxidant potential and dark pigmentation of these black chickpea landraces are more likely associated with flavan-3-ols and conjugated phenolic acids than with anthocyanin accumulation.

Therefore, whereas the relatively high catechin content detected in these black chickpea landraces supports the broader evidence that pigmented chickpeas generally possess enhanced phenolic richness, our results indicate that this distinction is specifically linked to the accumulation of flavan-3-ols and phenolic acid derivatives.

Beyond their technological properties, the investigated black chickpea flours may represent promising functional ingredients for the development of antioxidant-rich food products, contributing to both nutritional quality and added value in sustainable agri-food systems.

3.6 | Color Parameters

Color in legume flours is a critical quality attribute, directly influencing consumer acceptance and marketability, and is strongly dependent on pigment composition, genotype, and processing conditions. Colorimetric analysis of SBC and RBC flours revealed statistically significant differences in key CIE Lab parameters (Table 6). RBC flour exhibited significantly higher lightness (L^*) than SBC, indicating a brighter appearance. Lightness in pulse flours is influenced by intrinsic compositional factors, such as pigment concentration, as well as physical properties including particle size distribution and light scattering (Abou Chehade et al. 2024). The higher L^* observed in RBC may therefore be associated with differences in cotyledon exposure and microstructural disruption during milling, which enhance reflectance.

No significant differences were observed for a^* parameter, indicating a comparable red–green chromatic component across samples, in agreement with the generally low and stable a* values reported for chickpea flours (Abou Chehade et al. 2024). In contrast, RBC showed significantly higher b* values and Chroma, reflecting a more intense yellow coloration. This is consistent with the presence of carotenoids, such as lutein and zeaxanthin, which contribute to the yellow/orange hue of chickpea seeds and have been reported at higher levels in pigmented

TABLE 6 | Color profile, physicochemical, and technological properties of whole Smooth Black Chickpea (SBC) and Rough Black Chickpea (RBC) flours.

	SBC	RBC
*L**	86.93 ± 0.01[b]	89.58 ± 0.01[a]
*a**	1.00 ± 0.01[a]	1.32 ± 0.01[a]
*b**	20.20 ± 0.03[b]	21.24 ± 0.01[a]
Chroma	20.22 ± 0.01[b]	21.28 ± 0.01[a]
Hue angle	81.17 ± 0.04[b]	86.44 ± 0.01[a]
Yellow index	33.19 ± 0.01[a]	33.87 ± 0.01[a]
Whiteness index	24.08 ± 0.01[a]	23.69 ± 0.01[a]
Browning index	26.38 ± 0.01[a]	27.22 ± 0.01[a]
pH	6.46 ± 0.19[a]	6.35 ± 0.20[a]
Bulk density (g/ml)	0.71 ± 0.10[a]	0.73 ± 0.11[a]
Water absorption index (g/g)	3.72 ± 0.59[b]	4.28 ± 0.71[a]
Water soluble index (g/100 g)	22.43 ± 1.12[b]	24.14 ± 3.48[a]
Water absorption capacity (g/g)	1.77 ± 0.16[a]	1.89 ± 0.22[a]
Oil absorption capacity (g/g)	1.76 ± 0.12[a]	1.79 ± 0.17[a]
Emulsion activity (%)	60.0 ± 0.2[a]	61.0 ± 1.6[a]
Emulsion stability (%)	69.0 ± 2.8[b]	74.0 ± 3.1[a]
Swelling capacity (%)	20.0 ± 0.6[b]	54.0 ± 1.5[a]
Least gelation concentration (flour %)	12.0 ± 0.2[a]	10.0 ± 0.1[b]

Note: Different superscript letters in the same row indicate statistically significant differences at $p < 0.05$.
Abbreviations: a*, redness/greenness; b*, yellowness; L*, lightness.

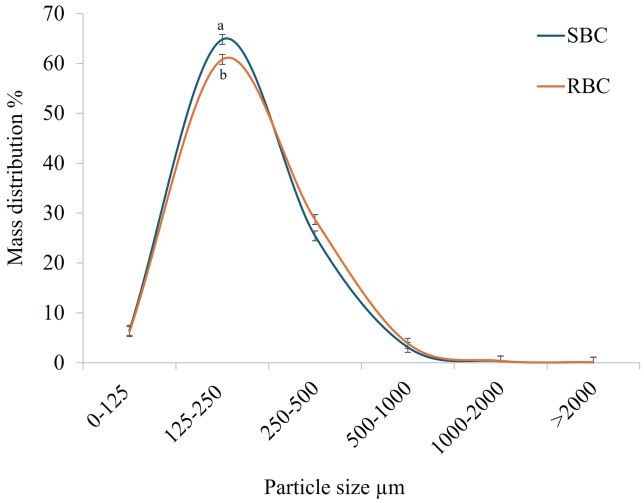

FIGURE 3 | Particle size distribution of Smooth Black Chickpea (SBC) and Rough Black Chickpea (RBC) flours.

genotypes (Skrzypczak et al. 2024). Accordingly, RBC also exhibited a higher Hue angle (H°), confirming a shift toward a more pronounced yellow tonality, in line with the increased *b** values and the relative contribution of yellow pigments (Akram et al. 2024).

No significant differences were found for the yellow index, whiteness index, and browning index, suggesting comparable levels of non-enzymatic browning and overall whiteness perception, which results from the combined interaction of *L**, *a**, and *b** coordinates rather than a single dominant parameter. Overall, the observed differences between SBC and RBC flours are consistent with genotype-related variation and the interplay between pigment composition and structural characteristics, which together influence the final color attributes of pulse flours.

3.7 | Particle Size, Physical–Chemical and Technological Properties

The particle size distribution of chickpea flours is a key parameter influencing hydration and surface-related functional properties. As reported in Figure 3, both SBC and RBC flours were predominantly characterized by the 125–250 µm fraction, accounting for 64.83% and 60.81%, respectively. However, RBC exhibited a significantly higher proportion of coarser particles (> 250 µm) compared to SBC ($p < 0.05$). Since both samples were subjected to the same milling conditions, these differences can be attributed to intrinsic seed characteristics, such as cotyledon structure and mechanical resistance. Similar genotype-dependent differences in milling behavior and particle size distribution have been reported by Ravi and Harte (2009) and further confirmed in a wide chickpea germplasm collection by Summo et al. (2019).

The two samples showed similar pH values (6.35–6.46) and bulk density (approximately 0.72 g/mL) (Table 6). The observed pH is consistent with typical values reported for chickpea flours and is favorable for maintaining protein solubility.

Interestingly, RBC showed significantly higher Water Absorption Index (WAI) (4.28 g/g) and Water Solubility Index (WSI) (24.14 g/100 g) than SBC. The variability in hydration-related properties across chickpea genotypes has been widely documented and is primarily attributed to differences in macromolecular organization (Summo et al. 2019). Although the higher WAI is consistent with the higher content of carbohydrates, including monosaccharides, disaccharides, and RFOs (Table 3), found in RBC flour, the higher WSI may also indicate enhanced molecular disintegration of starch and protein fractions during milling.

Water Absorption Capacity (WAC) and Oil Absorption Capacity (OAC) are critical parameters for the development of legume-based food systems. As shown in Table 6, RBC exhibited a slightly higher WAC (1.89 g/g) compared to SBC (1.77 g/g), values that fall within the range reported for chickpea flours depending on variety and composition (Ravi and Bhattacharya 2004; Ravi and Bhattacharya 2006). The slightly higher WAC observed in RBC may be partially associated with differences in dietary fiber composition. Previous studies have shown that chickpea varieties differ significantly in fiber structure and physicochemical properties, which can influence water retention capacity (Wang and Toews 2011). In addition, black chickpea fractions

have been reported to be particularly rich in dietary fiber and bioactive compounds, which may contribute to water binding and matrix structuring (Costantini et al. 2021).

Despite similar Emulsion Activity (EA) (~60%), RBC exhibited significantly higher Emulsion Stability (ES) (74%) compared to SBC (69%). This suggests differences in the interfacial properties of macromolecules, likely related to protein composition and interactions with other constituents. Genotype-dependent variability in protein functionality and technological behavior has been widely observed in chickpea (Summo et al. 2019). Furthermore, the presence of phenolic compounds in pigmented chickpeas may influence protein functionality through non-covalent interactions, potentially contributing to improved emulsion stability, creating a more rigid and stable viscoelastic film that prevents droplet coalescence (Tang et al. 2025; Kavur et al. 2025).

The most pronounced technological difference between the two flours was observed in swelling capacity. As reported in Table 6, RBC showed a markedly higher swelling capacity (54%) compared to SBC (20%), indicating a greater ability of this flour to absorb and retain water upon heating. This behavior can be attributed to intrinsic differences in starch structural organization. Genotype-dependent variations in starch properties and their interactions with proteins have been shown to strongly influence swelling behavior and water uptake in chickpea flours (Milán-Noris et al. 2019; Summo et al. 2019). Moreover, particle size effects on swelling behavior have also been recognized in other pulse flours, where particle size reduction or structural loosening enhances hydration indices and thermal transitions during cooking or pasting processes (Badia-Olmos et al. 2023). Consistently, RBC also showed a lower least gelation concentration (10% w/v) than SBC (12% w/v), indicating a greater efficiency in forming structured networks at lower concentrations. This functional advantage is likely related to more effective intermolecular interactions within the matrix, as previously described for chickpea flour systems (Milán-Noris et al. 2019; Summo et al. 2019). Similar genotype-dependent behavior has been documented in studies comparing chickpea cultivars, where structural and compositional differences markedly affected gelation, viscosity, and viscoelastic characteristics of resulting pastes and gels (Badia-Olmos et al. 2023).

3.8 | Principal Component Analysis of Chemical and Technological Data

The PCA statistical elaboration of chemical and technological data (Figure 4) explains 84.03% of the total variance and reveals a clear relationship between the compositional and technological properties of black chickpea flours. PC1 (70.81% of the total variance) separates samples according to proteins, fibers, total minerals, and total phenolics content for SBC samples, to matrices enriched in soluble carbohydrates and technological properties for RBC samples. Variables such as oil absorption capacity (OAC), emulsion activity (EA), emulsion stability (ES), water absorption index (WAI), water absorption capacity (WAC), bulk density (BD), swelling capacity (SC), and soluble sugars cluster on the positive side of PC1 and are strongly associated with RBC samples. This indicates that these samples exhibit enhanced interfacial and hydration-related functional properties, likely

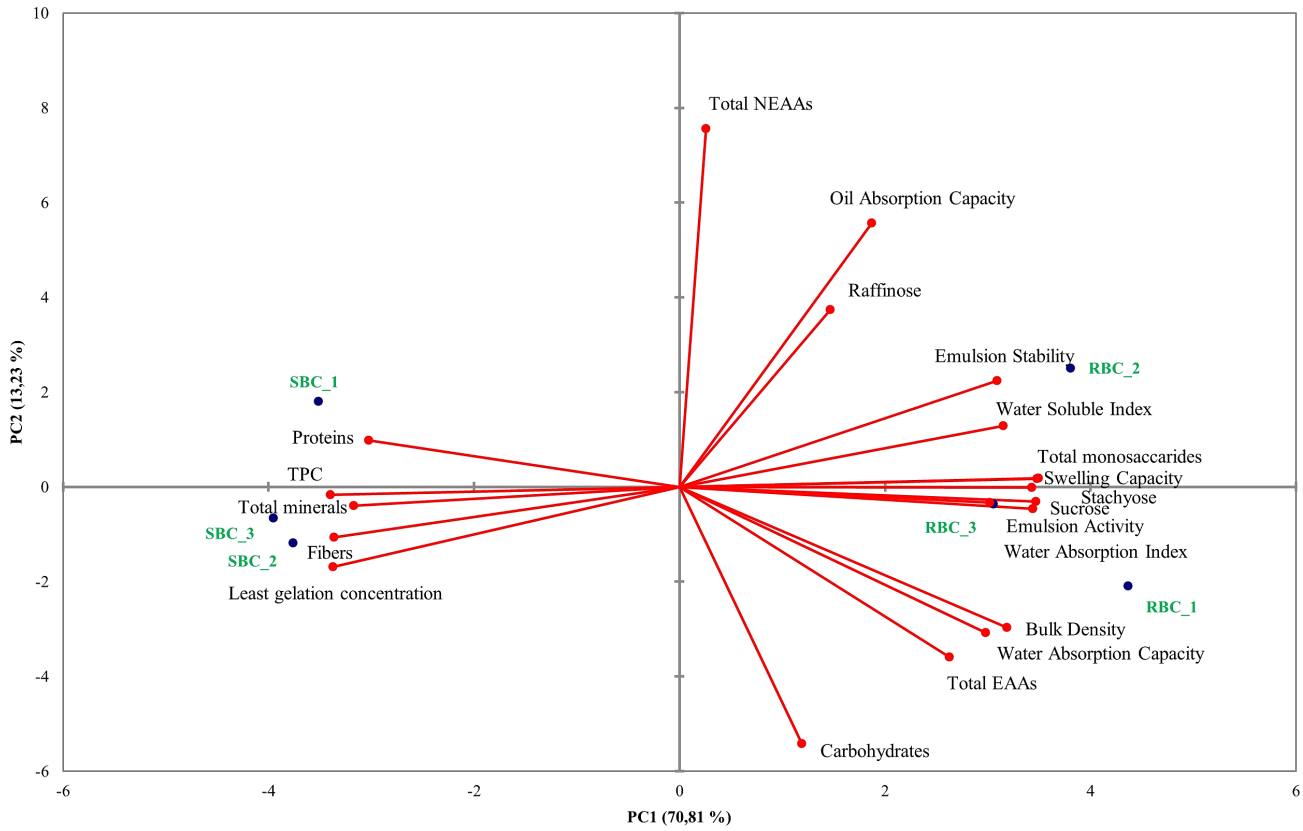

FIGURE 4 | PCA loading plot of chemical and techno-functional data of Smooth Black Chickpea (SBC) and Rough Black Chickpea (RBC) flours.

driven by higher levels of soluble carbohydrates. In contrast, SBC samples are positioned on the negative side of PC1 and correlate with proteins, fibers, minerals, and total phenolic compounds, suggesting a compositional profile less associated with emulsifying and oil-binding functionalities. PC2 (13.23% of the total variance) further differentiates samples based on amino acid-related variables (Total EAAs and NEAAs) and hydration behavior. The biplot reveals a clear trade-off between hydration-related properties and interfacial functionalities (emulsifying and lipid-binding capacities), indicating that compositional variability directly governs the technological performance of the flours.

In relation to these findings, the observed differences indicate that RBC flour may be more suitable for structured and high-moisture food systems requiring strong water absorption and gelation, whereas SBC flour may be better suited for formulations requiring more moderate hydration and functional performance. Moreover, the observed differences are consistent with broader literature showing that chickpea genotype, seed coat characteristics, and processing-induced microstructural changes all strongly influence technological behavior, which are highly relevant factors for the development of novel legume-based food applications.

4 | Conclusions

This study provides a comprehensive characterization of two neglected Sicilian black chickpea landraces, highlighting their potential as nutritionally valuable and technologically versatile ingredients for sustainable food systems. Both RBC and SBC flours exhibited balanced macronutrient composition, relevant levels of essential amino acids (with methionine as the limiting amino acid), and mineral contents comparable to those reported for conventional chickpea varieties, confirming their value as nutrient-dense legumes.

Their carbohydrate profiles, particularly the abundance of raffinose family oligosaccharides, emphasize their potential contribution to prebiotic dietary components. Phenolic profiling revealed the presence of shikimic acid, hydroxybenzoic and cinnamic acid derivatives, and catechin, with whole flours showing higher concentrations than dehulled ones. These compounds are associated with antioxidant activity, supporting the potential use of black chickpea flours as functional ingredients.

Despite broadly similar compositional profiles, RBC and SBC displayed distinct technological properties, confirming that even moderate compositional differences can significantly affect technological performance. RBC was characterized by higher levels of soluble carbohydrates and exhibited superior hydration properties, swelling capacity, emulsion stability, and lower gelation thresholds, indicating suitability for high-moisture, structured, and gel-based food systems. In contrast, SBC, with slightly higher protein and dietary fiber content, may be more appropriate for applications requiring controlled hydration and firmer textures.

These findings support the valorization of traditional black chickpea landraces as an ingredient for the development of innovative, sustainable, and nutritionally enhanced legume-based foods. However, further studies are needed to assess their technological performance, including viscosity, pasting, and rheological properties, as well as their functional properties in complex food systems and their biological quality, including protein digestibility and the bioavailability of essential amino acids. These aspects are crucial for optimizing food formulations and fully exploiting the nutritional and technological potential of these underutilized genetic resources.

Author Contributions

Marco Torre: investigation, formal analysis, data curation, writing – original draft, visualization. **Olimpia Pitirollo:** methodology, formal analysis, writing – original draft. **Roberto Laganà Vinci:** investigation, data curation. **Antonella Cavazza:** data curation, writing – review and editing. **Francesco Cacciola:** methodology, writing – review and editing. **Jens J. Sloth:** resources, writing – review and editing. **Charlotte Jacobsen:** resources, writing – review and editing. **Federico Casanova:** validation, writing – review and editing. **Antonella Verzera:** conceptualization, resources, writing – review and editing. **Fabrizio Cincotta:** conceptualization, resources, writing – review and editing, project administration, supervision.

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The authors have nothing to report.

Ethics Statement

The authors have nothing to report.

Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

References

Abdelaziz, S., H. M. Al Yousef, A. S. Al-Qahtani, W. H. B. Hassan, O. I. Fantoukh, and M. A. El-Sayed. 2020. "Phytochemical Profile, Antioxidant and Cytotoxic Potential of *Parkinsonia aculeata* L. Growing in Saudi Arabia." *Saudi Pharmaceutical Journal* 28, no. 9: 1129–1137. https://doi.org/10.1016/j.jsps.2020.08.001.

Abou Chehade, L., S. Tavarini, M. F. Bozzini, et al. 2024. "Agronomic and Phytochemical Characterization of Chickpea Local Genetic Resources for the Agroecological Transition and Sustainable Food Systems." *Agronomy* 14, no. 10: 2229. https://doi.org/10.3390/agronomy14102229.

Adebo, J. A. 2025. "Chemical Composition, Antioxidant Activity, Functional, Pasting, and Thermal Properties of Selected Bean Flours." *Legume Science* 7, no. 3: e70053. https://doi.org/10.1002/leg3.70053.

Adeyanju, A. A., P. O. Emmanuel, A. I. Adetunji, and O. A. Adebo. 2025. "Nutritional, Pasting, Rheological, and Thermal Properties of Sorghum–Okara Composite Flours and Porridges." *International Journal of Food Science and Technology* 60, no. 1: vvae021. https://doi.org/10.1093/ijfood/vvae021.

Akram, S., M. F. Afzal, K. Anwer, et al. 2024. "Nutraceutical Properties, Biological Activities, and Industrial Applications of Chickpea Protein." *Cogent Food & Agriculture* 10, no. 1: 2338653. https://doi.org/10.1080/23311932.2024.2338653.

ASABE. 2008. "Method of Determining and Expressing Fineness of Feed Materials by Sieving." Publ. S319. 4 Am Soc Agric Biol Eng.

AOAC INTERNATIONAL. 2023. *Official Methods of Analysis of AOAC INTERNATIONAL*. 22nd ed. AOAC INTERNATIONAL.

Badia-Olmos, C., L. Laguna, C. M. Haros, and A. Tárrega. 2023. "Techno-Functional and Rheological Properties of Alternative Plant-Based Flours." *Food* 12, no. 7: 1411. https://doi.org/10.3390/foods12071411.

Begum, N., Q. U. Khan, L. G. Liu, W. Li, D. Liu, and I. U. Haq. 2023. "Nutritional Composition, Health Benefits and Bio-Active Compounds of Chickpea (*Cicer Arietinum* L.)." *Frontiers in Nutrition* 10: 1218468. https://doi.org/10.3389/fnut.2023.1218468.

Brun, P., M. Camacho, F. Perea, M. J. Rubio, and D. N. Rodríguez-Navarro. 2024. "Characterization of Spanish Chickpea Genotypes (*Cicer arietinum* L.): Proximate, Mineral, and Phenolic Compounds Composition." *European Food Research and Technology* 250, no. 4: 1007–1016. https://doi.org/10.1007/s00217-023-04437-0.

Costantini, M., C. Summo, M. Faccia, F. Caponio, and A. Pasqualone. 2021. "Kabuli and Apulian Black Chickpea Milling by-Products as Innovative Ingredients to Provide High Levels of Dietary Fibre and Bioactive Compounds in Gluten-Free Fresh Pasta." *Molecules* 26, no. 15: 4442. https://doi.org/10.3390/molecules26154442.

Daba, S. D., P. Panda, U. K. Aryal, A. M. Kiszonas, S. M. Finnie, and R. J. McGee. 2025. "Proteomics Analysis of Round and Wrinkled Pea (*Pisum Sativum* L.) Seeds During Different Development Periods." *Proteomics* 25, no. 3: 2300363. https://doi.org/10.1002/pmic.202300363.

Dadi, F., A. Taha, L. Sales Queiroz, et al. 2025. "Effects of Ultrasound Treatment on Emulsifying Properties of Pea Protein Isolates Obtained From Four Different Pea Flour Varieties." *Food* 14, no. 9: 1634. https://doi.org/10.3390/foods14091634.

Dinali, M., R. Liyanage, M. Silva, et al. 2024. "Fibrous Structure in Plant-Based Meat: High-Moisture Extrusion Factors and Sensory Attributes in Production and Storage." *Food Reviews International* 40, no. 9: 2940–2968. https://doi.org/10.1080/87559129.2024.2309593.

Du, S. K., H. Jiang, X. Yu, and J. L. Jane. 2014. "Physicochemical and Functional Properties of Whole Legume Flour." *LWT- Food Science and Technology* 55, no. 1: 308–313. https://doi.org/10.1016/j.lwt.2013.06.001.

Elango, D., W. Wang, M. Thudi, S. Sebastiar, B. R. Ramadoss, and R. K. Varshney. 2022. "Genome-Wide Association Mapping of Seed Oligosaccharides in Chickpea." *Frontiers in Plant Science* 13: 1024543. https://doi.org/10.3389/fpls.2022.1024543.

El-Azaz, J., and H. A. Maeda. 2025. "The Multilayered Regulation of Aromatic Amino Acid Biosynthesis in Plants." *Trends in Biochemical Sciences* 50: 1051–1071. https://doi.org/10.1016/j.tibs.2025.07.008.

Emerald, F. M. E., H. A. Pushpadass, M. Manjunatha, et al. 2020. "Modelling Approaches for Predicting Moisture Transfer During Baking of Chhana Podo (Milk Cake) Incorporated With Tikhur (*Curcuma Angustifolia*) Starch." *Journal of Food Measurement and Characterization* 14, no. 6: 2981–2997. https://doi.org/10.1007/s11694-020-00543-9.

European Commission. 2011. "Regulation (EU) No 1169/2011 of the European Parliament and of the Council on the Provision of Food Information to Consumers." https://eurlex.europa.eu/eli/reg/2011/1169/oj.

European Commission. 2023. "Commission Regulation (EU) 2023/915 of 25 April 2023 on Maximum Levels for Certain Contaminants in Food and Repealing Regulation (EC) no 1881/2006." *Official Journal of the European Union* 119: 103–157. http://data.europa.eu/eli/reg/2023/915/oj.

FAO. 2016. *The State of Food and Agriculture: Climate Change, Agriculture and Food Security*. The State of Food and Agriculture Series. FAO.

Flory, J., R. Xiao, Y. Li, H. Dogan, M. J. Talavera, and S. Alavi. 2023. "Understanding Protein Functionality and Its Impact on Quality of Plant-Based Meat Analogues." *Food* 12, no. 17: 3232. https://doi.org/10.3390/foods12173232.

Foschia, M., S. W. Horstmann, E. K. Arendt, and E. Zannini. 2017. "Legumes as Functional Ingredients in Gluten-Free Bakery and Pasta Products." *Annual Review of Food Science and Technology* 8: 75–96. https://doi.org/10.1146/annurev-food-030216-030045.

Ghelichi, S., A. D. M. Sørensen, M. Hajfathalian, S. L. Holdt, and C. Jacobsen. 2025. "Screening Enzymatic Extracts of *Palmaria Palmata* Based on Composition and Bioactivity." *Algal Research* 89: 104048. https://doi.org/10.1016/j.algal.2025.104048.

Godschalk-Broers, L., G. Sala, and E. Scholten. 2022. "Meat Analogues: Relating Structure to Texture and Sensory Perception." *Food* 11, no. 15: 2227. https://doi.org/10.3390/foods11152227.

Grdeń, P., and A. Jakubczyk. 2023. "Health Benefits of Legume Seeds." *Journal of the Science of Food and Agriculture* 103, no. 11: 5213–5220. https://doi.org/10.1002/jsfa.12585.

Hacisalihoglu, G., G. White, and V. Salters. 2025. "Characterization of Seed Quality Traits Within 61 Chickpea (*Cicer arietinum*) Genotypes: Ionomes and Daily Values." *Seeds* 4, no. 1: 15. https://doi.org/10.3390/seeds4010015.

Hernández-Ruiz, R. G., X. C. Olivares-Ochoa, Y. Salinas-Varela, et al. 2025. "Phenolic Compounds and Anthocyanins in Legumes and Their Impact on Inflammation, Oxidative Stress, and Metabolism: Comprehensive Review." *Molecules* 30, no. 1: 174. https://doi.org/10.3390/molecules30010174.

Huamaní-Perales, C., J. Vidaurre-Ruiz, W. Salas-Valerio, D. M. Cabezas, and R. Repo-Carrasco-Valencia. 2024. "A Review of Techno-Functional Properties of Legume Proteins and Their Potential for Development of New Products." *European Food Research and Technology* 250, no. 8: 2069–2092. https://doi.org/10.1007/s00217-024-04536-6.

Jenisha, J. J., P. Vengatesh, P. P. Chidambaram, M. Samuel, and R. Arunraj. 2026. "Raffinose Family Oligosaccharides Metabolic Gene Expression Profiling in Chickpea During Seed Germination Under Abiotic Stress and Exogenous Application of ABA and GA." *Journal of Plant Biochemistry and Biotechnology* 35: 414–420. https://doi.org/10.1007/s13562-026-01035-5.

Jha, U. C., H. Nayyar, M. Thudi, R. Beena, P. V. Vara Prasad, and K. H. Siddique. 2024. "Unlocking the Nutritional Potential of Chickpea: Strategies for Biofortification and Enhanced Multinutrient Quality." *Frontiers in Plant Science* 15: 1391496. https://doi.org/10.3389/fpls.2024.1391496.

Kaur, M., and N. Singh. 2005. "Studies on Functional, Thermal and Pasting Properties of Flours From Different Chickpea (*Cicer arietinum* L.) Cultivars." *Food Chemistry* 91, no. 3: 403–411. https://doi.org/10.1016/j.foodchem.2004.06.015.

Kavur, P. B., D. Ö. Şahin, E. Çavdaroğlu, et al. 2025. "Techno-Functional and Antioxidant Properties of Chickpea Proteins Interacted With Green Tea Phenolics–Exploring Benefits for Gel and Emulsion-Based Vegan Foods." *International Journal of Biological*

Macromolecules 331, no. 1: 148366. https://doi.org/10.1016/j.ijbiomac.2025.148366.

Kumar, N., S. Hong, Y. Zhu, et al. 2025. "Comprehensive Review of Chickpea (*Cicer Arietinum*): Nutritional Significance, Health Benefits, Techno-Functionalities, and Food Applications." *Comprehensive Reviews in Food Science and Food Safety* 24, no. 2: e70152. https://doi.org/10.1111/1541-4337.70152.

Kumar, Y., V. S. Sharanagat, L. Singh, and S. Mani. 2020. "Effect of Germination and Roasting on the Proximate Composition, Total Phenolics, and Functional Properties of Black Chickpea (*Cicer Arietinum*)." *Legume Science* 2, no. 1: e20. https://doi.org/10.1002/leg3.20.

Laganà Vinci, R., K. Arena, F. Rigano, F. Cacciola, P. Dugo, and L. Mondello. 2024. "Prediction of Retention Data of Phenolic Compounds by Quantitative Structure Retention Relationship Models Under Reverse-Phase Liquid Chromatography." *Journal of Chromatography A* 1730: 465146. https://doi.org/10.1016/j.chroma.2024.465146.

La-ongkham, O., K. Wadeesirisak, and S. Chantorn. 2025. "Exploring Effects of Chickpea-Derived Crude Oligosaccharides on Gut Microbiota and Their Potential in Cashew Nut Yogurt-Like Product Development." *Applied Food Research* 5, no. 2: 101160. https://doi.org/10.1016/j.afres.2025.101160.

Lisciani, S., S. Marconi, C. Le Donne, et al. 2024. "Legumes and Common Beans in Sustainable Diets: Nutritional Quality, Environmental Benefits, Spread and Use in Food Preparations." *Frontiers in Nutrition* 11: 1385232. https://doi.org/10.3389/fnut.2024.1385232.

Macar, T. K., O. Macar, and D. İ. Mart. 2017. "Variability in Some Biochemical and Nutritional Characteristics in Desi and Turkish Kabuli Chickpea (*Cicer Arietinum* L.) Types." *Celal Bayar University Journal of Science* 13, no. 3: 677–680. https://doi.org/10.18466/cbayarfbe.339330.

Milán-Noris, A. K., J. De la Rosa-Millan, and S. O. Serna-Saldivar. 2019. "Comparative Analysis of Techno-Functional Properties, Starch Digestion and Protein Quality of Pigmented Chickpea Flours." *International Journal of Food Science and Technology* 54, no. 6: 2288–2299. https://doi.org/10.1111/ijfs.14144.

Nam, T., A. Kim, and Y. Oh. 2023. "Effectiveness of Chickpeas on Blood Sugar: A Systematic Review and Meta-Analysis of Randomized Controlled Trials." *Nutrients* 15, no. 21: 4556. https://doi.org/10.3390/nu15214556.

Nezami, A., A. A. Mahmoodi, J. Nabati, M. Mohammadi, and A. Hasanfard. 2023. "Feasibility Study of Cultivating Desi-Type Chickpea Genotypes in Cold and Temperate Regions." *Legume Science* 5, no. 2: e179. https://doi.org/10.1002/leg3.179.

Perea-Escobar, C. D., L. Londoño-Hernández, J. R. Benavente-Valdés, N. Balagurusamy, J. C. Contreras Esquivel, and A. Y. Hernández-Almanza. 2025. "Incorporation of Protein Alternatives in Bakery Products: Biological Value and Techno-Functional Properties." *Applied Sciences* 15, no. 20: 11279. https://doi.org/10.3390/app152011279.

Pitirollo, O., M. Grimaldi, C. Corradini, S. Pironi, and A. Cavazza. 2023. "HPAEC-PAD Analytical Evaluation of Carbohydrates Pattern for the Study of Technological Parameters Effects in Low-FODMAP Food Production." *Molecules* 28, no. 8: 3564. https://doi.org/10.3390/molecules28083564.

Ravi, R., and S. Bhattacharya. 2004. "Flow Behaviour of Chickpea (*Cicer arietinum* L.) Flour Dispersions: Effect of Additives." *Journal of Food Engineering* 65, no. 4: 619–624. https://doi.org/10.1016/j.jfoodeng.2004.02.030.

Ravi, R., and S. Bhattacharya. 2006. "The Time-Dependent Rheological Characteristics of a Chickpea Flour Dispersion as a Function of Temperature and Shear Rate." *International Journal of Food Science and Technology* 41, no. 7: 751–756. https://doi.org/10.1111/j.1365-2621.2006.01040.x.

Ravi, R., and J. B. Harte. 2009. "Milling and Physicochemical Properties of Chickpea (*Cicer arietinum* L.) Varieties." *Journal of the Science of Food and Agriculture* 89, no. 2: 258–266. https://doi.org/10.1002/jsfa.3435.

Rocchetti, G., L. Lucini, J. M. L. Rodriguez, F. J. Barba, and G. Giuberti. 2019. "Gluten-Free Flours From Cereals, Pseudocereals and Legumes: Phenolic Fingerprints and *In Vitro* Antioxidant Properties." *Food Chemistry* 271: 157–164. https://doi.org/10.1016/j.foodchem.2018.07.176.

Salaria, S., T. Lawrence, and D. Thavarajah. 2025. "Nutritional Composition of Chickpea (*Cicer Arietinum* L.) Grown in Winter Cropping Systems: A New Sustainable Legume Opportunity." *Legume Science* 7, no. 3: e70034. https://doi.org/10.1002/leg3.70034.

Schmidt, H. D. O., and V. R. D. Oliveira. 2023. "Overview of the Incorporation of Legumes Into New Food Options: An Approach on Versatility, Nutritional, Technological, and Sensory Quality." *Food* 12, no. 13: 2586. https://doi.org/10.3390/foods12132586.

Scordia, D., P. Guarnaccia, F. Calderone, et al. 2024. "Adoption of Cereal–Legume Double Cropping Toward More Sustainable Organic Systems in the Mediterranean Area." *Agronomy* 14, no. 4: 772. https://doi.org/10.3390/agronomy14040772.

Segev, A., H. Badani, Y. Kapulnik, I. Shomer, M. Oren-Shamir, and S. Galili. 2010. "Determination of Polyphenols, Flavonoids, and Antioxidant Capacity in Colored Chickpea (*Cicer arietinum* L.)." *Journal of Food Science* 75, no. 2: S115–S119. https://doi.org/10.1111/j.1750-3841.2009.01477.x.

Shahid, N., I. Ul-Haq, G. A. Nayik, et al. 2024. "Physicochemical and Bioactive Traits of Black Chickpea (*Cicer Arietinum*) as Affected by Germination-Induced Modifications." *International Journal of Food Properties* 27, no. 1: 165–179. https://doi.org/10.1080/10942912.2023.2301566.

Skrzypczak, K., A. Wirkijowska, K. Przygoński, K. Terpiłowski, and A. Blicharz–Kania. 2024. "Quality and Functional Properties of Bread Containing the Addition of Probiotically Fermented *Cicer arietinum*." *Food Chemistry* 448: 139117. https://doi.org/10.1016/j.foodchem.2024.139117.

Sreerama, Y. N., D. A. Neelam, V. B. Sashikala, and V. M. Pratape. 2010. "Distribution of Nutrients and Antinutrients in Milled Fractions of Chickpea and Horse Gram: Seed Coat Phenolics and Their Distinct Modes of Enzyme Inhibition." *Journal of Agricultural and Food Chemistry* 58, no. 7: 4322–4330. https://doi.org/10.1021/jf903101k.

Sreerama, Y. N., V. B. Sashikala, and V. M. Pratape. 2010. "Variability in the Distribution of Phenolic Compounds in Milled Fractions of Chickpea and Horse Gram: Evaluation of Their Antioxidant Properties." *Journal of Agricultural and Food Chemistry* 58, no. 14: 8322–8330. https://doi.org/10.1021/jf101335r.

Summo, C., D. De Angelis, L. Ricciardi, et al. 2019. "Nutritional, Physico-Chemical and Functional Characterization of a Global Chickpea Collection." *Journal of Food Composition and Analysis* 84: 103306. https://doi.org/10.1016/j.jfca.2019.103306.

Tang, S., X. Yang, C. Wang, and C. Wang. 2025. "Effects of Polyphenols on the Structure, Interfacial Properties, and Emulsion Stability of Pea Protein: Different Polyphenol Structures and Concentrations." *Molecules* 30, no. 8: 1674. https://doi.org/10.3390/molecules30081674.

Vilakazi, B., P. L. Mafongoya, A. O. Odindo, and M. M. Phophi. 2025. "The Role of Neglected Grain Legumes in Food and Nutrition Security and Human Health." *Sustainability* 17, no. 1: 350. https://doi.org/10.3390/su17010350.

Wang, N., and R. Toews. 2011. "Certain Physicochemical and Functional Properties of Fibre Fractions From Pulses." *Food Research International* 44, no. 8: 2515–2523. https://doi.org/10.1016/j.foodres.2011.03.012.

Webb, D., H. Dogan, Y. Li, and S. Alavi. 2023. "Use of Legume Flours and fiber for Tailoring Structure and Texture of Pea Protein-Based

Extruded Meat Alternatives." *Journal of Food Science* 88, no. 1: 57–71. https://doi.org/10.1111/1750-3841.16397.

World Health Organization, and United Nations University. 2007. *Protein and Amino Acid Requirements in Human Nutrition*. Vol. 935. World Health Organization.

Xiao, S., Z. Li, K. Zhou, and Y. Fu. 2023. "Chemical Composition of Kabuli and Desi Chickpea (*Cicer Arietinum* L.) Cultivars Grown in Xinjiang, China." *Food Science & Nutrition* 11, no. 1: 236–248. https://doi.org/10.1002/fsn3.3056.

Yanni, A. E., S. Iakovidi, E. Vasilikopoulou, and V. T. Karathanos. 2023. "Legumes: A Vehicle for Transition to Sustainability." *Nutrients* 16, no. 1: 98. https://doi.org/10.3390/nu16010098.

Zhong, L., G. Wu, Z. Fang, et al. 2019. "Characterization of Polyphenols in Australian Sweet Lupin (*Lupinus angustifolius*) Seed Coat by HPLC-DAD-ESI-MS/MS." *Food Research International* 116: 1153–1162. https://doi.org/10.1016/j.foodres.2018.09.061.