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# Evaluating the Sustainable Processing on Nutritional, Functional, Phenolics, In Vitro Protein Digestibility, and Antioxidant Bioavailability of Himalayan Peas

Pallavi Phian[1,2] | Mahesh Gupta[1,2]

[1]Food and Nutraceutical Laboratory, Dietetics and Nutrition Technology Division, CSIR-Institute of Himalayan Bioresource Technology, Palampur, Himachal Pradesh, India | [2]Academy of Scientific and Innovative Research (AcSIR), Ghaziabad, Uttar Pradesh, India

**Correspondence:** Mahesh Gupta (mgupta@ihbt.res.in)

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## ABSTRACT

This study systematically evaluates the effects of four processing techniques, autoclaving, roasting, boiling, and sonication, on the nutritional composition, functional properties, protein digestibility, and phenolic profiles of Himalayan green pea (*Pisum sativum* L.) and green chickpea (*Cicer arietinum*). Processing significantly enhanced protein content (23%–26% increase) and dietary fiber levels, with roasting yielding the highest improvements (15.74% in peas, 11.03% in chickpeas). Protein digestibility was noticeably improved, reaching up to 98% following autoclaving and roasting, indicating enhanced bioavailability through high-pressure thermal treatments. Phenolic analysis revealed elevated catechin concentrations post-processing (170.93 μg/100 mg in peas; 132.72 μg/100 mg in chickpeas), suggesting improved antioxidant potential. However, reductions in rutin and gallic acid were observed, particularly in green chickpeas (raw: 274.43 μg/100 mg rutin; 58.74 μg/100 mg gallic acid). Conversely, esterified trans-ferulic acid increased in autoclaved green peas (93.91 μg/100 mg), and roasting promoted accumulation of bound catechin, gallic acid, and trans-ferulic acid. Essential amino acids such as leucine and lysine were also elevated after roasting (GPW: 7.26 and 6.51 mg/100 g; GCW: 5.98 and 5.50 mg/100 g, respectively). These findings emphasize the potential of targeted processing methods to enhance the nutritional and functional quality of Himalayan legumes, supporting their application in functional food development. Further research is warranted to optimize processing conditions for maximal retention of bioactive compounds.

## 1 | Introduction

Food security is a major concern nowadays. In particular, protein malnutrition has to be treated urgently. Food manufacturers are becoming more interested in plant-based proteins. Therefore, legume crops have the potential to be utilized as high-quality, climate-change-resistant, and sustainable sources of plant-based protein and phenolic compounds (Chaudhary et al. 2023). Legumes are plants of the family Fabaceae that play a crucial role in agriculture, nutrition, and culinary traditions worldwide (Stagnari et al. 2017). This family is mainly characterized by their fruit; legumes are not only nutrient-rich but also environmentally sustainable, producing up to seven times less greenhouse gas emissions (Adams et al. 2016). These crops retain nitrogen-rich residue after harvesting, which is beneficial for the subsequent crop that is planted in its place since they can generate their own nitrogen from the environment and do not require nitrogen fertilizer (Stagnari et al. 2017). The Food and Agriculture Organization (FAO) announced the International Year of Pulses in 2016. In order to prevent malnutrition and ensure food security, because these crops are drought-resistant species, they can be especially helpful in arid regions where food security is frequently a problem. Because legumes retain their nutritional value even after being dried and kept for extended periods, they can also reduce food waste.

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Green pea (*Pisum sativum* L.) and green chickpea (*Cicer arietinum* L.) are nutrient-rich legumes valued for their high protein content (20%–25%), fiber (5%–9%), and essential micronutrient content, including vitamins C, K, folate, and minerals like potassium, magnesium, and iron (Dahl et al. 2012). Chickpeas contribute over 25% to global output and are cultivated across varied Indian agro-climatic zones (Muehlbauer and Sarker 2017), while green peas thrive in the temperate belts of Himachal Pradesh, notably Kangra, Mandi, and Shimla (Chaudhary and Singh 2020; Babu et al. 2021). Both support metabolic health by aiding glycemic regulation, lowering cholesterol, and promoting beneficial gut flora (Singh et al. 2017). Their antioxidant-rich profiles help mitigate risks of chronic ailments such as cardiovascular disease, breast cancer, and hyperlipidemia (Cryne et al. 2012; Zhang et al. 2015; Singh et al. 2016). Despite shared benefits, they differ in agronomy and composition. Green peas, a cool-season crop, are tender with a mildly sweet taste, whereas green chickpeas, harvested immature, are more fibrous and iron-dense, offering advantages for anemia prevention and maternal nutrition. Phenolic compounds in both exist in free, esterified (soluble conjugated), and insoluble-bound forms. Green chickpeas exhibit higher raw levels of rutin and gallic acid, while green peas retain more esterified phenolics after processing (Jung et al. 2002; Robbins 2003). These distinctions highlight their complementary roles in dietary planning and functional food innovation, especially within Himalayan agriculture and health-focused applications. Plants may contain phenolic acids in three different forms: free form (esterified) soluble conjugated, and insoluble-bound phenolic. But in comparison to the free versions, esterified phenolics have not been studied as much (Jung et al. 2002; Robbins 2003). Researchers have demonstrated that antioxidants present in conjugates are well-known for their anti-inflammatory properties both in vitro and in vivo studies (Sato et al. 2011). Additionally, esterified and bound phenolics may be crucial in helping the colon absorb antioxidants when the bacterial microbiota releases them. A thorough examination of all types of free, esterified, and bound phenolics is therefore required. It is also commonly recognized that proteins are digested to form tiny peptides and amino acids during gastrointestinal digestion, allowing for their absorption. Certain peptides have the ability to fight oxidative stress and scavenge free radicals within the human body (Carrasco-Castilla et al. 2012). The aim of this study is to analyze the effect of these processing methods on nutritional, functional, and phenolic compounds such as free, esterified, and bound. In vitro protein digestibility and bioavailability of antioxidant activity of green pea and green chickpea. Encouraging the use and processing of legumes as consumer food products is one strategy to help accomplish the Sustainable Development Goal (target 2: zero hunger, food security, eradicating malnutrition, and sustainable agriculture) by 2030 (Acquah et al. 2021).

## 2 | Material and Methods

### 2.1 | Chemicals and Reagents

The chemicals and reagents are high-performance liquid chromatography (HPLC) and analytical grade purchased from Hi-Media Laboratories Pvt. Ltd. (India). FC (Folin–Ciocalteu) reagent, sodium carbonate, sodium hydroxide, aluminum chloride, and potassium per sulfate. α-amylase, pepsin, pancreatin, and OX-Bile from Millipore Sigma (India). Bradford reagent, 2, 2′-azino-bis-(3-ethyl-benzothiazoline-6-sulfonate) (ABTS), and 2,2-diphenyl-1-picrylhydrazyl (DPPH) were purchased from Merck India Pvt. Ltd.

### 2.2 | Procurement of Raw Material and Sample Preparation

The grains of green peas (*Pisum sativum L.*) and green chickpea (*Cicer arietinum L.*) were procured from the local market of Palampur, Himachal Pradesh, India. To remove extraneous materials such as dirt, dust, stones, damaged seeds, and immature grains, all the samples were manually cleaned. The cleaned legume grains were then pulverized using a cutting miller (Retsch, SM-100) in a controlled laboratory environment. The resulting flour was stored in airtight containers at room temperature until further use. Prior to processing, legume grains were soaked overnight in distilled water at a ratio of 1:2 (w/v). Post-soaking, the samples underwent four distinct processing treatments: Autoclaving, Roasting, Boiling, and Sonication. Each method was applied under standardized laboratory conditions to ensure consistency across samples. In autoclave, pressure for 15 min at 15 lb psi at 121°C, boiling at 90°C for 90 min, open pan roasting was done at 170°C for 20 min, and sonication using a water bath sonicator at 55°C for 60 min. After all processing, the samples were freeze-dried and pulverized to get fine flours for further analysis.

### 2.3 | Nutritional Analysis

The legume samples were analyzed by (AOAC 2000) official method of the Association of Official Analytical Chemists for moisture, fat, crude protein, ash content, and crude fiber. The total carbohydrates were evaluated using the difference method, that is, [Total *Carbohydrates* (%) = 100 − (*Moisture content* + *Ash content* + *Protein content* + *Fat content*)]. Dietary fiber and resistant starch contents were evaluated using the Megazyme Total Dietary Fiber kit and the Megazyme Resistant Starch Assay kit, respectively. Phytic acid content was quantified using the Megazyme Phytic Assay kit. The total carotenoid content of both legumes was determined following the method described by Silva da Rocha et al. (2015).

### 2.4 | Functional Properties

#### 2.4.1 | Water Absorption

Oil absorption and water solubility index were determined as described by Bhatt et al. (2021). Water absorption index (WAI), OAI (g/g), and WSI% were calculated using equations.

$$\text{WAI (g/g)} = \frac{\text{Wt3} - \text{Wt1}}{\text{Wt}} \quad (1)$$

$$\text{OAI (g/g)} = \frac{\text{Wt3} - \text{Wt1}}{\text{Wt}} \quad (2)$$

$$(\text{WSI\%}) = \frac{\text{Wt2} - \text{Wt1}}{\text{Wt}} * 100 \quad (3)$$

where $Wt_1$ is the empty petri dish weight, $Wt_2$ is the residual weight after drying and petri plate derived from the supernatant, $Wt_3$ is the residual weight after centrifugation and Wt. is the initial weight of the sample.

#### 2.4.2 | Water Activity ($a_w$)

The $a_w$ of samples was analyzed by using $a_w$ meter (4TE dew point water, Aqua lab); all the experiments were carried out in triplicate.

### 2.5 | CIELAB Colorimetric Analysis

Color profile values of $L^*$, $a^*$, and $b^*$ were recorded with a reflectance Chroma-Meter (KONICA MINOLTA CR-400 CIE, 1971). The color parameters are specified as ($L^*$) luminosity evaluated on the 0 (black) to 100 (white) scale, $a^*$ ($+a^*$ is denoted red and $-a^*$ is denoted green) $b^*$ indicate yellow ($+b^*$) and blue ($-b^*$) values of the both pea grains samples raw and processed.

### 2.6 | Extraction Procedure for Free, Esterified, and Bound Phenolic Compounds

The extraction of free phenolics was carried out using the method reported by Sharma and Gupta (2023) with slight modifications to optimize the extraction procedure. After the extraction process, collected supernatants were pooled together, and ethanol was removed by using rota evaporation. 2.0 pH was adjusted using 2N HCl. Subsequently, free phenolics were extracted using ethyl acetate. The resulting fragment of ethyl acetate was then evaporated using a rota evaporator (BUCHI Switzerland) and redissolved in MS-grade methanol. Further extraction has been reported by Prakash et al. (2019). After hydrolyzing, the remaining aqueous phase was treated for an hour under $N_2$ atmosphere with 2M NaOH. After that, 2N HCl was used to acidify the resulting extract to (2.0 pH) and it was further extracted using ethyl acetate three times. The extracted fraction was pooled together, and ethyl acetate was evaporated to dryness and reconstituted in methanol and named as esterified phenolics. The remaining residue for bound phenolics was extracted with 2M NaOH for 2 h at room temperature, and after that, it was acidified to 2.0 pH using 4N hydrochloric acid and centrifuged at 6000 rpm for 5 min at 4°C (Remi India Pvt. Ltd). The supernatant was extracted with ethyl acetate three times, and ethyl acetate was evaporated using a rota evaporator to dryness and reconstituted in MS-grade methanol.

### 2.7 | HPLC Method Used for the Investigation of Free, Esterified, and Bound Phenolic

High Performance Liquid chromatography consisted of an Agilent Infinity II HPLC (Agilent Technologies, USA) and a DAD (diode array detector) with a C18 RRHD (2.1 mm × 150 mm, 1.8 μm) separation column LIChrospher100. The solvent (A) is water with 0.1% formic acid and solvent (B) is acetonitrile with 0.05% formic acid, respectively, using as a mobile phase in the maintained gradient system. Different methods of gradient elution were used to separate the desired phenolics by varying the percentage of mobile phase A and B. Combinations of gradient series A of (0–2 min 95% A; 2–6 min, 85% A; 6–9 min, 65% A; 9–13 min, 55% A; 13–17 min, 70% A; 17–20 min, 80% A; 20–22 min, and 95% A) were optimized, resulting in precise separation of phenolics. The injection volume also played a crucial role in peak separation with an injection volume range of (2–10 μL) at a flow rate of 1 mL/min, although several absorption wavelengths from 210 to 280 nm were monitored. Resulting chromatograms were examined at 280 nm, which reveal a promising signal-to-noise ratio.

### 2.8 | In Vitro Digestibility

With minor modifications, a three-stage in vitro digestion model that mimics the oral stage, gastric stage, and intestinal conditions was used in this work followed by Minekus et al. (2014). The simulated intestinal fluid (SIF), simulated gastric fluid (SGF), and simulated salivary fluid (SSF) were among the electrolyte stock solutions that were made.

*In oral phase*, 5 g solid/5 mL of liquid was taken and 3.5 mL of SSF was added and kept for 10 min for activation. Then 75 U/mL α-amylase solution, 25 μL of 0.3 M $CaCl_2$, and 975 μL of distilled $H_2O$ was added to the suspension and incubated for 2 min for pre-warming of all reagents and enzyme at 37°C.

*In gastric phase*, 10 mL of oral bolus was taken and 7.5 mL of SGF (2000 U/mL pepsin solution), 5 μL of 0.3 M $CaCl_2$, and 0.695 μL distilled $H_2O$ were added and adjusted to 3.0 pH with the help of 1 M HCl and incubated for 2 h at 37°C under shaking conditions.

*In intestinal phase*, 20 mL of Chyme was taken and 11 mL SIF (100 U/mL Pancreatin), 160 mM porcine bile, 40 μL of 0.3 M $CaCl_2$, and pH was adjusted to 7.0 with 1 M NaOH and 1.31 mL distilled water was added.

#### 2.8.1 | Dialysate Absorption

Given that the intestinal digesting stage is where antioxidant absorption occurs mostly, the resultant mixture was transferred to dialysis membrane (Dialysis Membrane-135, MW cut off: 12,000–14,000 Da) placed in an Erlenmeyer flask with 50 mL of PBS buffer for incubation in a rotary shaker for (2 h at 37°C). The PBS buffer together with compounds that passed through the membrane was used as a substitute for the raw material absorbed in the colon during digestion along with the chemicals that went through the membrane (Dialysate) (Gawlik-Dziki 2012). By heating the samples in a water bath for 10 min at 90°C, the reaction of digestive enzymes was terminated. Tubes were centrifuged at 4000 g at 4°C for 10 min. The collected supernatant was separated and stored for further analysis at −20°C.

#### 2.8.2 | Protein Digestibility (%)

The content of protein was assessed using the method of Cryne et al. (2012) calculated as follows:

$$\text{IVPD}(\%) = (X - Y)/X \times 100 \quad (4)$$

where $X$ is the content of protein before digestion, and $Y$ is the content of residual protein after digestion.

#### 2.8.3 | Antioxidant Activity

To assess the radical scavenging potential of the samples, both DPPH and ABTS assays were employed, reported by Phull et al. (2024). Digested fractions (1 mL) were mixed with (1 mL) 0.2 mM 2,2-diphenyl-1-picrylhydrazyl (DPPH) in 95% of methanol. The mix was incubated in the dark at room temperature for 30 min. Absorbance was recorded by using Thermo Scientific GENESYS UV spectrophotometer. Cuvette at 517 nm, with ascorbic acid as a positive control and methanol as a blank. 2,2′azino-bis(3-ethylbenzothiazoline-6-sulfonic acid) radical cation was prepared through oxidation of ABTS by using potassium persulfate ($K_2S_2O_8$). Prepare 7 mM ABTS (500 μL) and 2.45 mM ($K_2S_2O_8$) potassium persulfate (500 μL), which was kept for 12–16 h in a dark place at ambient temperature. Afterwards, distilled $H_2O$ was added to this working solution and diluted until it reached an absorbance of $0.90 \pm 0.05$ to $0.70 \pm 0.05$ at 734 nm. Absorbance was noted in Thermo Scientific GENESYS UV spectrophotometer (cuvette). The percent inhibition was calculated for DPPH and ABTS antioxidant activity of the sample by using the equation given below:

$$\text{DPPH (Inhibition\%)} = (\text{Abs of control} - \text{Abs of sample}/\text{Abs of control}) * 100 \quad (5)$$

$$\text{ABTS (Inhibition\%)} = (\text{Abs of Control} - \text{Abs of sample}/\text{Abs of control}) * 100 \quad (6)$$

### 2.9 | Free Amino Acid Composition

The Waters Acquity (Ultra Performance Liquid Chromatography) UPLC-H class system was used to analyze the free amino acid content of green pea and green chickpea. A 600-controller pump, an online degasser, a photodiode array detector (PDA), binary solvent management, a column heater, and an autosampler are all included in the system. For separations, a Water BEH C18 column (2.1 × 100 mm, 1.7 μm particle size) was combined with an appropriate guard column.

In mobile phase A, triethylamine and sodium acetate (0.14 mol/L) were utilized, while glacial acetic acid and methanol (90:10) were employed to lower the pH to 6.7. In mobile phase B, acetonitrile was utilized (Dev and Gupta 2024; Kumari et al. 2022). Both samples were derivatized with O-phthalaldehyde and run through a membrane syringe filter with a pore size of 0.45 μm prior to being injected into the system.

### 2.10 | Fatty Acid Analysis

The fatty acid composition of green pea and green chickpea was determined by trans esterifying the fats with hexane to produce fatty acid methyl esters (FAME), as previously described by Dev and Gupta (2024) Using the Soxhlet equipment, 5 g of both unprocessed and processed pea were refluxed in hexane for 16 h at 60°C to extract oil. A rotary evaporator was then used to evaporate the solvent at 40°C with lowered pressure. The obtained dried samples were then injected onto the GC column after being redissolved in 1 mL of *n*-hexane of Gas Chromatography (GC) grade. Helium was used as the carrier gas in a GC to analyze the hexane extracts using a Shimadzu GCMS-QP2010 system fitted with a GC column SGE BP-20 (30 m length, inner diameter 0.25 mm × 0.25 μm film thickness). After 4 min at 70°C, the column temperature was raised to 220°C at a rate of 4°C per minute, and it was then kept there for 5 min. A split ratio of 1:50, an injector temperature of 220°C, and a column flow rate of 1.10 mL per minute were all established. The ion source temperature was set at 200°C, while the interface temperature was set at 220°C. The mass range of 40–600 mass units was scanned using electronic ionization at 70 eV. Two microliters of the sample were injected. Wiley 7 and NIST 02 mass spectrum libraries were used for chemical identifications.

### 2.11 | Statistical Analysis

All experiments were conducted in triplicate, and results were expressed as mean ± standard deviation. Statistical significance was determined using one-way ANOVA followed by Tukey (HSD) test ($p \leq 0.05$).

## 3 | Results and Discussion

### 3.1 | Composition Analysis of (*Pisum sativum* L.) and (*Cicer arietinum* L.)

The proximate makeup of these samples is displayed in Table 1. Total carbohydrates predominate in all samples, followed by protein and fat. These findings are comparable with de Almeida Costa et al. (2006). Carbohydrates make up the majority of the constituent group in legumes as compared to the raw fraction of legumes. Processed legumes showed significantly ($p < 0.05$) higher concentrations in GPW autoclave (66.41%) as compared to raw and other processing methods used. Similarly, in GCW autoclave, the highest was 66.72%. In comparison to raw flour, the content of protein increased up to 4% after autoclaving GPW (22.64%–26.03%) and GCW (22.40%–26.38%), and similar results were reported by Martineau-Côté et al. (2023). Except for raw and autoclaved, the fat content was found higher in both green pea and green chickpea after different processing methods, that is, GPW boiling (2.55%) and GCW roasting (5.56%). It was observed that the content of fat increased after the cooking process due to the loss of water-soluble components (Wang et al. 2010; Seena et al. 2006). Green chickpea flour contains a higher concentration of fat compared to green pea flour. The lipid content in legumes plays a critical role in the formation of amylose-lipid complexes, which can influence starch gelatinization subsequently reduce starch bioavailability. Additionally,the enzyme lipoxygenase catalyzes the oxidation of unsaturated fatty acids into volatile compounds. This reaction, particularly prominent in high-fat legume flours such as soy, may pose challenges in food formulation due to the development of off- flavors and reduced sensory acceptability. Therefore, the elevated fat levels in green chickpea flours may impact both its functional properties and its suitability for incorporation into certain food products since it can alter the flavor and shelf life of various

food items (Guichard 2002). The moisture content values ranged from 9.32% to 1.46% for GCW and GPW (8.49%–3.35%). The lower moisture content in processed flours likely results from freeze-drying, while soaking and heat treatments may further influence reductions in ash and crude fiber content. The entire amount of minerals is indicated by the ash content; it is likely that minerals leach out in the soaking and different cooking treatments. In cooked legume seed flour, ash content was significantly lower than that of raw seed, that is, GPW (3.36%–2.09%) and GCW (3.95%–2.46%). Similar results were observed by Marconi et al. (2000). A reduction in ash content following thermal processing indicates the migration or loss of mineral constituents during cooking. Among the various treatments applied to green pea and green chickpea flours, autoclaving resulted in the most prominent decrease in ash levels, suggesting substantial mineral leaching. Dietary fiber, defined as the fibrous structural components of plant cell walls, also declined significantly post-processing. Compared to raw flour, fiber content in green pea (GPW) decreased from 6.13% to 4.44%, while green chickpea flour (GCW) showed a reduction from 9.06% to 8.46%. This decline is attributed to the leaching of soluble fiber fractions during heat treatment.

### 3.2 | Effect of Processing Method on Functional Properties of Green Pea and Green Chickpea Flour

The functional characteristics of green pea flour and chickpea flour were examined in Table 2. These characteristics of flours are crucial in the production of many food products. The process of preparing food products is significantly influenced by the water absorption index (WAI) of flour, which also affects other functional and sensory qualities. The WAI of boiling followed by autoclaving of both samples GPW (4.14–4.05 g/g) and GCW (4.26–4.04 g/g) shows higher WAI as compared to other processing methods. Legume flours' cooking and food processing

**TABLE 1** | Proximate analysis of green pea flour (GPW), green chickpea flour (GCW) on dry basis.

| Sample | Moisture (%) | Crude fat (%) | Crude Protein (%) | Ash (%) | Crude Fiber (%) | Carbohydrate (%) |
|---|---|---|---|---|---|---|
| GPW raw | $8.49 \pm 0.20^{e}$ | $1.76 \pm 0.04^{a}$ | $22.64 \pm 0.40^{a}$ | $3.36 \pm 0.17^{c}$ | $6.13 \pm 0.18^{b}$ | $62.76 \pm 0.19^{ab}$ |
| GPW Autoclave | $3.35 \pm 0.00^{b}$ | $0.81 \pm 0.47^{a}$ | $26.03 \pm 0.20^{c}$ | $2.73 \pm 0.01^{b}$ | $4.44 \pm 0.18^{a}$ | $66.41 \pm 0.89^{c}$ |
| GPW Roasting | $5.51 \pm 0.34^{d}$ | $2.15 \pm 1.76^{c}$ | $24.63 \pm 0.20^{b}$ | $2.51 \pm 0.01^{b}$ | $5.81 \pm 0.97^{b}$ | $61.74 \pm 0.88^{ab}$ |
| GPW Boiling | $4.20 \pm 1.19^{c}$ | $2.55 \pm 1.06^{cd}$ | $23.93 \pm 0.20^{a}$ | $2.46 \pm 0.01^{b}$ | $5.42 \pm 1.09^{ab}$ | $61.37 \pm 0.66^{ab}$ |
| GPW Sonication | $3.97 \pm 0.44^{c}$ | $2.29 \pm 0.67^{bc}$ | $22.53 \pm 0.17^{a}$ | $2.09 \pm 0.07^{a}$ | $5.78 \pm 0.61^{b}$ | $63.03 \pm 1.22^{b}$ |
| GCW raw | $9.32 \pm 0.00^{f}$ | $3.62 \pm 0.14^{de}$ | $22.40 \pm 0.28^{a}$ | $3.95 \pm 0.54^{d}$ | $9.06 \pm 0.30^{c}$ | $60.69 \pm 0.31^{a}$ |
| GCW Autoclave | $3.81 \pm 0.00^{c}$ | $3.60 \pm 0.78^{de}$ | $26.38 \pm 0.20^{c}$ | $2.77 \pm 0.06^{b}$ | $8.50 \pm 0.26^{c}$ | $66.72 \pm 072^{c}$ |
| GCW Roasting | $3.90 \pm 0.09^{c}$ | $5.56 \pm 1.11^{f}$ | $24.63 \pm 0.20^{b}$ | $3.54 \pm 0.03^{c}$ | $8.53 \pm 0.76^{c}$ | $61.45 \pm 2.71^{ab}$ |
| GCW Boiling | $4.09 \pm 1.19^{c}$ | $4.57 \pm 0.29^{ef}$ | $24.28 \pm 0.20^{b}$ | $2.46 \pm 0.12^{b}$ | $8.46 \pm 0.46^{c}$ | $61.75 \pm 2.7^{ab}$ |
| GCW Sonication | $1.46 \pm 0.35^{a}$ | $5.31 \pm 0.61^{f}$ | $23.46 \pm 0.35^{a}$ | $3.91 \pm 0.05^{d}$ | $8.62 \pm 0.52^{c}$ | $61.91 \pm 0.39^{ab}$ |

*Note:* Resulted values are represented as mean ± SD $n = 3$ green pea flour (GPW) and green chickpea flour (GCW). Data in the same column with the different lower case letters are significantly different at ($p < 0.05$.) by Tukey (HSD) test.

**TABLE 2** | Functional properties of green pea flour (GPW), green chickpea flour (GCW) on dry basis.

| Sample | WAI ($g g^{-1}$) | OAI ($g g^{-1}$) | WSI% | $a_w$ | Bulk density ($g mL^{-1}$) |
|---|---|---|---|---|---|
| GPW raw | $3.21 \pm 0.06^{c}$ | $2.11 \pm 0.14^{b}$ | $15.92 \pm 1.15^{c}$ | $0.38 \pm 0.01^{d}$ | $0.70 \pm 0.01^{a}$ |
| GPW Autoclave | $4.05 \pm 0.00^{e}$ | $2.26 \pm 0.03^{d}$ | $11.54 \pm 0.25^{b}$ | $0.05 \pm 0.01^{a}$ | $0.77 \pm 0.02^{c}$ |
| GPW Roasting | $3.68 \pm 0.13^{d}$ | $2.33 \pm 0.02^{c}$ | $12.01 \pm 1.35^{b}$ | $0.15 \pm 0.01^{c}$ | $0.74 \pm 0.02^{b}$ |
| GPW Boiling | $4.14 \pm 0.09^{e}$ | $2.15 \pm 0.03^{b}$ | $9.62 \pm 1.70^{a}$ | $0.03 \pm 0.00^{a}$ | $0.78 \pm 0.01^{cd}$ |
| GPW Sonication | $3.78 \pm 0.03^{d}$ | $2.43 \pm 0.04^{e}$ | $12.86 \pm 0.19^{b}$ | $0.04 \pm 0.00^{a}$ | $0.76 \pm 0.00^{c}$ |
| GCW raw | $2.84 \pm 0.02^{a}$ | $1.88 \pm 0.14^{a}$ | $19.79 \pm 0.63^{d}$ | $0.45 \pm 0.01^{e}$ | $0.70 \pm 0.01^{a}$ |
| GCW Autoclave | $4.04 \pm 0.02^{e}$ | $2.26 \pm 0.02^{c}$ | $12.47 \pm 0.87^{b}$ | $0.03 \pm 0.00^{a}$ | $0.81 \pm 0.01^{d}$ |
| GCW Roasting | $3.73 \pm 0.05^{d}$ | $2.12 \pm 0.07^{b}$ | $11.59 \pm 0.13^{b}$ | $0.08 \pm 0.00^{b}$ | $0.77 \pm 0.01^{c}$ |
| GCW Boiling | $4.26 \pm 0.06^{f}$ | $2.23 \pm 0.01^{bc}$ | $8.25 \pm 0.54^{a}$ | $0.05 \pm 0.02^{a}$ | $0.77 \pm 0.01^{c}$ |
| GCW Sonication | $3.07 \pm 0.01^{b}$ | $2.16 \pm 0.04^{b}$ | $13.06 \pm 0.06^{b}$ | $0.03 \pm 0.00^{a}$ | $0.76 \pm 0.01^{c}$ |

*Note:* Resulted values are represented as mean ± SD, $n = 3$ green pea flour (GPW) and green chickpea flour (GCW). Data in the same column with the different lower case letters are significantly different at ($p < 0.05$.) by Tukey (HSD) test.

**TABLE 3** | Dietary fiber, resistant starch, and phytic acid content on a dry basis.

| Sample | Total dietary fiber (%) | Soluble dietary fiber (%) | Insoluble dietary fiber (%) | Phytic acid (g/100 g) | Resistant starch (g/100 g) | Carotenoids (μg/g) |
|---|---|---|---|---|---|---|
| GPW raw | 6.03 ± 0.24$^{a}$ | 1.68 ± 1.05$^{ab}$ | 4.34 ± 0.96$^{a}$ | 0.86 ± 0.00$^{cd}$ | 10.93 ± 0.02$^{b}$ | 22.11 ± 1.28$^{a}$ |
| GPW Autoclave | 7.86 ± 0.68$^{a}$ | 1.33 ± 0.26$^{ab}$ | 6.52 ± 0.42$^{bc}$ | 0.44 ± 0.01$^{a}$ | 11.19 ± 0.03$^{bc}$ | 42.63 ± 1.07$^{de}$ |
| GPW Roasting | 15.74 ± 2.83$^{c}$ | 6.90 ± 1.16$^{f}$ | 9.10 ± 1.42$^{d}$ | 0.95 ± 0.01$^{cd}$ | 9.73 ± 0.01$^{a}$ | 32.72 ± 3.11$^{b}$ |
| GPW Boiling | 11.55 ± 0.5$^{b}$ | 3.95 ± 0.65$^{de}$ | 7.59 ± 0.74$^{cd}$ | 0.61 ± 0.00$^{ab}$ | 9.12 ± 0.02$^{a}$ | 38.83 ± 2.41$^{cd}$ |
| GPW Sonication | 10.12 ± 0.73$^{b}$ | 2.67 ± 0.07$^{bc}$ | 7.44 ± 0.67$^{bc}$ | 0.89 ± 0.00$^{cd}$ | 12.15 ± 0.03$^{cd}$ | 24.88 ± 0.51$^{a}$ |
| GCW raw | 6.78 ± 0.71$^{a}$ | 0.83 ± 0.18$^{a}$ | 5.94 ± 0.80$^{ab}$ | 1.03 ± 0.05$^{de}$ | 9.43 ± 0.02$^{a}$ | 22.50 ± 0.98$^{a}$ |
| GCW Autoclave | 8.83 ± 0.82$^{b}$ | 1.32 ± 0.17$^{ab}$ | 7.39 ± 0.72$^{bc}$ | 0.75 ± 0.24$^{bc}$ | 11.80 ± 0.04$^{bc}$ | 43.72 ± 1.95$^{e}$ |
| GCW Roasting | 11.03 ± 1.68$^{d}$ | 1.62 ± 0.09$^{ab}$ | 9.73 ± 1.35$^{d}$ | 1.18 ± 0.01$^{e}$ | 11.97 ± 0.03$^{c}$ | 35.62 ± 0.29$^{bc}$ |
| GCW Boiling | 10.09 ± 2.57$^{c}$ | 3.57 ± 2.23$^{de}$ | 7.76 ± 3.89$^{bc}$ | 0.98 ± 0.01$^{cde}$ | 10.30 ± 0.02$^{b}$ | 56.13 ± 1.64$^{f}$ |
| GCW Sonication | 9.18 ± 0.02$^{c}$ | 3.47 ± 1.25$^{de}$ | 6.36 ± 0.44$^{a}$ | 0.98 ± 0.02$^{cde}$ | 9.29 ± 0.01$^{a}$ | 72.01 ± 0.44$^{g}$ |

*Note:* Resulted values are represented as mean ± SD, $n = 3$ green pea flour (GPW) and green chickpea flour (GCW). Data in the same column with the different lower case letters are significantly different at ($p < 0.05$.) by Tukey (HSD) test.

qualities are closely connected to their moisture content. Similar results were reported by Wani and Kumar (2014). The increased WAI of both dry green pea flour and chickpea flour can be ascribed to the higher concentration of hydrophilic components like soluble fiber (Akubor and Badifu 2004). WSI of green pea raw and green chickpea raw was observed as 15.92% and 19.79%. OAI of processed legume flour increased after processing in comparison to raw flour. The stronger binding of lipids by hydrophobic proteins suggests that the side chains of non-polar amino acids are responsible for binding the paraffin chains of fats. According to Kinsella and Melachouris (1976), legume flour with a high oil absorption index is probably due to its non-polar side chains, which have more protein molecules available. Water activity of both legumes has no significant difference due to freeze drying after processing. The bulk density of a sample, which is related to the weight of the sample can support if enabled to rest directly on one another, may be used to determine the packing needs for that sample. There was no significant difference found in the bulk density of both legume samples. Similar results were reported by Wani and Kumar (2014).

### 3.3 | Phytic Acid, Resistant Starch, Carotenoid Content, and Dietary Fiber

Legumes had a higher content of phytic acid as shown in Table 3. Roasted flour exhibited elevated levels of phytic acid, with concentrations measured at (1.19 g/100 g) in green chickpea and (0.95 g/100 g) green pea. In contrast, autoclaving significantly reduced phytic acid content, yielding values of 0.81 ± 0.31 g/100 g in green chickpea and 0.43 ± 0.01 g/100 g in green pea. These findings suggested that thermal processing, particularly autoclaving, is effective in reduce phytic acid levels and potentially improving mineral digestibility. Similar results were reported by Wang et al. (2008) among six different pea species (0.64–0.83 g/100 g). Although phytic acid may have some positive health effects, excessive intake can be harmful because of its ability to form chemical complexes with minerals especially iron and zinc, which decreases the absorption of those elements through the diet (Amarakoon et al. 2012). InGCW roasting resistant starch value increased (11.9 ± 0.03 g/100 g) after roasting followed by autoclaving, boiling and sonication in comparison to raw whereas, in GPW resistant starch value increased after sonication (12.15 ± 0.03 g/100 g) followed by autoclaving and decreased after roasting and boiling treatment (Woo and Seib 2002). The carotenoid content of green pea significantly increased after processing using autoclaving (42.63 μg/g), whereas in green chickpea after sonication, the carotenoids content also increases (72.0 μg/g). Total dietary fiber content was found significantly higher in roasted seed flour of both legumes, that is, GPW roasting (15.74% ± 2.83%) and GCW roasting (11.03% ± 1.68%). In comparison to processed seed flour, raw seeds flour has significantly lower content of IDF, that is, green pea and green chickpea raw (4.34% ± 0.96% and 5.94% ± 0.80%). Insoluble dietary fiber is not easily solubilized in water and goes undigested to the large intestine, whereas soluble dietary fiber is easily solubilized in the water and develops viscous solutions. The main role of insoluble dietary fiber is adding bulk to the diet and provide satiety and lower the density of energy (Lattimer and Haub 2010). GPW Roasting (6.90% ± 1.16%) and GCW Boiling (3.57% ± 2.23%) has higher content of soluble dietary fiber. It has been suggested that SDF's capacity to produce viscous solutions slows down stomach emptying, lowering the amount of glucose and triglycerides that are absorbed throughout the intestine. However, many of researches highlighted that IDF play role in improving the sensitivity of insulin, hence maybe contributing in the prevention of type 2 diabetes as reported by Kaczmarczyk et al. (2012).

### 3.4 | HPLC Quantification of Free, Esterified, and Bound Phenolic

Nine known phenolic acids such as gallic acid, catechin, caffeic acid, *t*-ferulic acid, p-coumaric acid, and rutin were evaluated in the extracts. Changes in phenolic compounds after using different

processing treatments, including autoclaving, boiling, roasting, and sonication, have been described. The amount of various phenolic components in raw and processed legumes varied in green pea extract. The main phenolic components were *t*-ferulic acid, gallic acid, and catechin. GPW raw, followed by autoclave, has the highest gallic acid (58.74 < 48.22 μg/100 mg) among all other processing methods. Catechin was one of the prevalent phenolic compounds, ranging from 170.93 < 132.72 < 110.14 < 88.56 μg/100 mg after roasting, followed by autoclaving, boiling, and sonication in free form. In green chickpea extract, gallic acid, catechin, and predominantly rutin were present in higher concentrations in raw samples, followed by boiling, sonication, autoclaving, and roasting (274.43 < 183.27 < 113.07 < 62.46 μg/100 mg) in free form. In esterified form, *t*-ferulic acid was found significantly higher after autoclave, sonication (93.91 and 51.71 μg/100 mg), and catechin increased after roasting (27.99 μg/100 mg) of GPW, alongside the degradation of protocatechuic acid and caffeic acid after processing. According to research, the most prevalent phenolic acid found in edible dry beans is ferulic acid, which also plays a structural role in the cross-linking of wall polymers described by Luthria and Pastor-Corrales (2006).

Bound phenolics of green pea catechin were significantly increased after processes followed by roasting, sonication, boiling, and autoclaving (29.20 < 23.55 < 16.49 < 11.03 μg/100 mg), *t*-ferulic roasting, sonication, and boiling (15.76 < 15.47 < 6.18 μg/100 mg) in comparison to raw and not quantified in the autoclaving process, whereas protocatechuic acid decreased after processing.

In GCW, eight phenolic compounds were evaluated in the resulted extracts after different processing treatments. Rutin was predominantly evaluated in raw (274.43 μg/100 mg), and significant decreases were observed after different processing. Gallic acid was found in raw and different processing treatments, with the highest being after the boiling process (119.90 μg/100 mg). Caffeic acid was present in high concentration (21.14 μg/100 mg) after processing in free form. Gallic acid and caffeic acid decreased due to heat, and catechin was found highest among other phenolic compounds, which was only present in raw (62.64 μg/100 mg) and degraded after processing treatments in esterified form, *t*-ferulic acid was highest after boiling. All the quantified bound phenolic compounds increased after processing treatments. p-Coumaric acid and syringic acid were only present in free and bound form. Previous studies have demonstrated that heat processing can help release bound phenolic acids due to weakened ester bonds between phenolics and cell wall polysaccharides (Dewanto et al. 2002). Complete profiles are provided in Tables 4 and 5.

### 3.5 | L a b Color Value

Among all the qualities of premium legumes, color is one of the most experimentally studied aspects, along with cost on the global market. The predominant green color of the pea flour was derived from the pea seeds. The primary colorant of green pea flour, chlorophyll, has been reported to be sensitive to pH and temperature (Koca et al. 2007). The color value of raw and processed GPW and GCW is presented in Figure 1a,b. The $L^*$ value increased in raw flour compared to processed flour in both green pea and green chickpea, 73.47 and 78.23. The boiling process decreases the luminosity. Conversely, the parameter $a^*$ was found to exhibit negative values in green pea flour (−5.45 raw and −1.32 boiling) and green chickpea flour (−4.13 raw and −0.10 boiling). This indicates that the flour was primarily green in color, and that its greenness decreased with increasing temperature due to the degradation of chlorophyll, which also affects heat-sensitive micronutrients such as vitamin C, folate, and certain polyphenols. Additionally, prolonged exposure to high temperatures can lead to leaching of water-soluble nutrients. The heating process results in an increase in $b^*$ value in comparison to raw; the autoclaved sample has a higher $b^*$ value in both samples, 25.54 and 20.04 in green pea and green chickpea, similar results reported by Younis et al. (2023).

### 3.6 | In Vitro Protein Digestibility in Raw and Processed Green Pea and Green Chickpea

Protein digestibility refers to how well protein can be broken down and absorbed in the digestive system. Processing treatments can denature proteins, making them more accessible to digestive enzymes. However, excessive cooking can also lead to the formation of cross-links that are resistant to digestion. IVPD (In Vitro Protein Digestibility) of both varieties of legumes is presented in Figure 2. Before and after processing treatments, the present study revealed that the high-pressure method increases the protein digestibility of GPW autoclave, followed by roasting, boiling, and sonication (98.54% < 95.67% < 91.66% < 90.42%). The cooking process by autoclaving increases on average up to 10%–15% in both legumes. It was found that the best optimization for GPW protein digestibility occurs during the autoclaving process. Additionally, GCW also shows the highest protein digestibility during the autoclaving process (98.08% < 95.23% < 94.67% < 89.68%), followed by boiling, roasting, and sonication, similar findings by Wang et al. (2008). Overall, as per results, high-temperature processing is found best among the methods of RAW, autoclaving, roasting, boiling, and sonication; autoclaving is the most favorable process for both GPW and GCW. This is due to higher IVPD through thermal processing, which may be linked to the breakdown of protein into smaller peptides and antinutritional compounds like tannins, phytates, and polyphenols in a variety of legumes, including kidney beans, chickpeas, and peas, as well as the inactivation of antinutritional proteins like lectins and trypsin inhibitors reported by Xu et al. (2016), Alonso et al. (2000) and Clemente et al. (2000). Protein conformational changes brought on by heat, such as protein aggregation due to increased hydrophobicity and the creation of disulfide bonds, may also make proteins less susceptible to proteolysis reported by Chau and Cheung (1997), Carbonaro et al. (1997), Carbonaro et al. (2000). Therefore, analysis should be done on how legumes' fundamental nutritional compositions and variations in protein constituents throughout digestion influence the whole digestibility of protein content. Improving protein digestibility through optimal processing treatments can enhance the nutritional quality of food, helping to combat malnutrition.

**TABLE 4** | Quantification of free, esterified, and bound phenolic compound in GPW on extract basis.

| Sample | Gallic acid (μg/100 mg) | Protocatechuic (μg/100 mg) | Chlorogenic acid (μg/100 mg) | Catechin (μg/100 mg) | Caffeic acid (μg/100 mg) | Syringic acid (μg/100 mg) | Rutin (μg/100 mg) | *p*-coumaric (μg/100 mg) | *t*-ferulic acid (μg/100 mg) |
|---|---|---|---|---|---|---|---|---|---|
| Free | | | | | | | | | |
| GPW raw | $58.74 \pm 6.52^{d}$ | $14.41 \pm 20.38^{a}$ | $4.93 \pm 0.56^{abc}$ | $30.95 \pm 2.52^{b}$ | $9.55 \pm 1.76^{c}$ | $2.07 \pm 2.93^{a}$ | NQ | $5.29 \pm 1.62^{bc}$ | NQ |
| GPW Autoclave | $48.22 \pm 4.76^{cd}$ | $2.72 \pm 0.29^{a}$ | $1.86 \pm 0.39^{ab}$ | $132.72 \pm 11.34^{c}$ | NQ | $3.21 \pm 4.54^{a}$ | $7.47 \pm 10.57^{abc}$ | $4.95 \pm 0.15^{bc}$ | NQ |
| GPW Roasting | $31.63 \pm 0.52^{b}$ | $0.82 \pm 1.16^{a}$ | $8.65 \pm 0.52^{d}$ | $170.93 \pm 2.25^{d}$ | $8.93 \pm 0.02^{c}$ | $5.07 \pm 0.03^{a}$ | $28.82 \pm 1.04^{c}$ | $7.86 \pm 3.97^{c}$ | $16.81 \pm 7.26^{de}$ |
| GPW Boiled | $39.16 \pm 5.40^{bc}$ | $7.55 \pm 2.50^{a}$ | $6.34 \pm 0.18^{bc}$ | $110.14 \pm 0.15^{c}$ | $5.84 \pm 0.11^{b}$ | NQ | $25.84 \pm 0.03^{bc}$ | $1.90 \pm 1.11^{a}$ | $11.37 \pm 2.99^{bcd}$ |
| GPW Sonication | $37.36 \pm 2.87^{a}$ | NQ | NQ | $88.56 \pm 0.73^{c}$ | $3.69 \pm 1.37^{bc}$ | NQ | NQ | $3.58 \pm 1.04^{abc}$ | $12.82 \pm 1.22^{bcd}$ |
| Esterified | | | | | | | | | |
| GPW raw | $3.11 \pm 4.40^{a}$ | $3.68 \pm 0.54^{a}$ | NQ | NQ | $4.03 \pm 0.28^{b}$ | $1.68 \pm 2.38^{a}$ | NQ | NQ | $22.62 \pm 1.72^{e}$ |
| GPW Autoclave | $4.40 \pm 0.20^{a}$ | $1.94 \pm 0.03^{a}$ | NQ | $12.09 \pm 0.96^{ab}$ | NQ | NQ | $14.01 \pm 19.81^{abc}$ | NQ | $93.91 \pm 0.28^{g}$ |
| GPW Roasting | $7.03 \pm 1.02^{a}$ | $0.71 \pm 0.02^{a}$ | $2.71 \pm 0.95^{ab}$ | $27.99 \pm 2.03^{ab}$ | $0.17 \pm 0.25^{a}$ | $5.09 \pm 0.18^{a}$ | $7.81 \pm 0.49^{abc}$ | NQ | NQ |
| GPW Boiled | $4.74 \pm 0.15^{a}$ | $0.31 \pm 0.44^{a}$ | NQ | $6.61 \pm 0.60^{ab}$ | NQ | NQ | $8.57 \pm 1.18^{abc}$ | NQ | $9.71 \pm 1.09^{bcd}$ |
| GPW Sonication | $8.37 \pm 0.35^{a}$ | $6.22 \pm 1.94^{a}$ | $2.76 \pm 3.91^{abc}$ | $17.95 \pm 12.38^{a}$ | NQ | NQ | $5.86 \pm 0.49^{abc}$ | NQ | $51.71 \pm 3.79^{f}$ |
| Bound | | | | | | | | | |
| GPW raw | $4.24 \pm 0.27^{a}$ | $15.47 \pm 0.07^{a}$ | NQ | $6.23 \pm 0.37^{ab}$ | $0.60 \pm 0.04^{a}$ | $1.82 \pm 0.02^{a}$ | NQ | NQ | $4.65 \pm 0.59^{ab}$ |
| GPW Autoclave | $0.67 \pm 0.47^{a}$ | NQ | NQ | $11.03 \pm 1.46^{a}$ | NQ | NQ | NQ | NQ | NQ |
| GPW Roasting | $0.73 \pm 0.55^{a}$ | $0.73 \pm 0.40^{a}$ | NQ | $29.20 \pm 1.03^{ab}$ | $1.01 \pm 0.11^{a}$ | NQ | NQ | NQ | $15.76 \pm 0.24^{de}$ |
| GPW Boiled | $7.94 \pm 1.20^{a}$ | $4.10 \pm 2.17^{a}$ | $2.81 \pm 3.98^{abc}$ | $16.49 \pm 11.28^{ab}$ | $0.25 \pm 0.35^{a}$ | $1.07 \pm 1.51^{a}$ | $3.18 \pm 0.93^{ab}$ | $1.16 \pm 0.02^{a}$ | $6.18 \pm 0.26^{a}$ |
| GPW Sonication | $1.75 \pm 0.10^{a}$ | $0.14 \pm 0.20^{a}$ | NQ | $23.55 \pm 4.08^{ab}$ | $1.02 \pm 0.99^{a}$ | $3.23 \pm 0.34^{a}$ | NQ | NQ | $15.47 \pm 1.62^{cde}$ |

*Note:* Resulted values are represented as mean ±SD, $n = 3$ green pea (GPW). Data in the same column with the different lower case letters are significantly different at ($p < 0.05$.) by Tukey (HSD) test.

**TABLE 5** | Quantification of free, esterified, and bound phenolic compounds in GCW on an extract basis.

| Sample | Gallic acid (μg/100 mg) | Protocatechuic (μg/100 mg) | Catechin (μg/100 mg) | Caffeic acid (μg/100 mg) | Syringic acid (μg/100 mg) | Rutin (μg/100 mg) | *p*-coumaric (μg/100 mg) | *t*-ferulic acid (μg/100 mg) |
|---|---|---|---|---|---|---|---|---|
| Free | | | | | | | | |
| GCW raw | 17.04 ± 0.93$^{c}$ | 0.56 ± 0.04$^{a}$ | 19.33 ± 0.54$^{ab}$ | 0.97 ± 0.02$^{a}$ | 5.65 ± 0.25$^{b}$ | 274.43 ± 3.64$^{h}$ | NQ | NQ |
| GCW Autoclave | 54.01 ± 12.49$^{e}$ | NQ | 158.16 ± 29.03$^{c}$ | 25.78 ± 10.12$^{b}$ | 3.24 ± 4.58$^{ab}$ | 113.07 ± 0.75$^{e}$ | 15.14 ± 12.00$^{bc}$ | NQ |
| GCW Roasting | 4.64 ± 1.04$^{abc}$ | 1.89 ± 1.76$^{ab}$ | NQ | 4.10 ± 2.01$^{a}$ | NQ | 62.46 ± 6.14$^{d}$ | 0.08 ± 0.12$^{a}$ | 3.16 ± 4.47$^{a}$ |
| GCW Boiled | 119.90 ± 0.87$^{f}$ | 3.58 ± 0.00$^{ab}$ | 11.59 ± 1.85$^{a}$ | 9.13 ± 2.34$^{a}$ | NQ | 183.27 ± 4.61$^{g}$ | 26.53 ± 4.46$^{c}$ | NQ |
| GCW Sonication | 36.27 ± 6.40$^{d}$ | NQ | NQ | 1.62 ± 1.20$^{a}$ | NQ | 135.89 ± 2.73$^{f}$ | 3.09 ± 3.01$^{ab}$ | 6.03 ± 8.54$^{abc}$ |
| Esterified | | | | | | | | |
| GCW raw | 16.17 ± 0.00$^{bc}$ | 0.50 ± 0.00$^{a}$ | 62.64 ± 39.68$^{b}$ | 21.14 ± 0.00$^{b}$ | NQ | 42.56 ± 0.67$^{c}$ | NQ | 19.49 ± 0.00$^{a}$ |
| GCW Autoclave | 1.03 ± 0.00$^{ab}$ | 0.81 ± 0.05$^{a}$ | NQ | 8.56 ± 0.31$^{a}$ | NQ | NQ | NQ | 18.49 ± 1.10$^{a}$ |
| GCW Roasting | 1.38 ± 0.11$^{ab}$ | 0.47 ± 0.05$^{a}$ | NQ | 3.08 ± 0.01$^{a}$ | NQ | 34.55 ± 0.43$^{c}$ | NQ | 7.28 ± 0.49$^{abc}$ |
| GCW Boiled | 1.91 ± 0.19$^{ab}$ | 0.46 ± 0.66$^{a}$ | NQ | 8.24 ± 0.89$^{a}$ | NQ | 17.08 ± 10.71$^{ab}$ | NQ | 15.77 ± 0.04$^{bcd}$ |
| GCW Sonication | 6.24 ± 0.16$^{abc}$ | NQ | NQ | 3.79 ± 0.00$^{a}$ | NQ | 42.28 ± 10.21$^{c}$ | NQ | 3.32 ± 4.59$^{a}$ |
| Bound | | | | | | | | |
| GCW raw | 1.25 ± 0.11$^{ab}$ | 1.84 ± 0.14$^{ab}$ | 0.61 ± 0.11$^{a}$ | NQ | 2.29 ± 0.03$^{ab}$ | NQ | NQ | 2.60 ± 0.32$^{a}$ |
| GCW Autoclave | 3.86 ± 0.29$^{abc}$ | NQ | 2.77 ± 0.01$^{a}$ | NQ | NQ | NQ | 0.45 ± 0.08$^{a}$ | 6.01 ± 0.76$^{a}$ |
| GCW Roasting | 3.30 ± 0.07$^{abc}$ | NQ | NQ | 0.96 ± 0.24$^{a}$ | NQ | NQ | 2.36 ± 0.36$^{ab}$ | NQ |
| GCW Boiled | 0.65 ± 0.53$^{a}$ | 0.47 ± 0.18$^{a}$ | NQ | 1.77 ± 0.14$^{a}$ | 3.39 ± 0.59$^{ab}$ | NQ | NQ | 17.09 ± 0.47$^{cd}$ |
| GCW Sonication | 2.60 ± 1.42$^{abc}$ | 0.22 ± 0.32$^{a}$ | 5.80 ± 0.46$^{a}$ | 0.03 ± 0.05$^{a}$ | NQ | NQ | 0.43 ± 0.61$^{a}$ | 4.69 ± 0.03$^{a}$ |

*Note:* Resulted values are represented as mean ± SD, $n = 3$ green chickpea (GCW). Data in the same column with the different lower case letters are significantly different at ($p < 0.05$.) by Tukey (HSD) test.

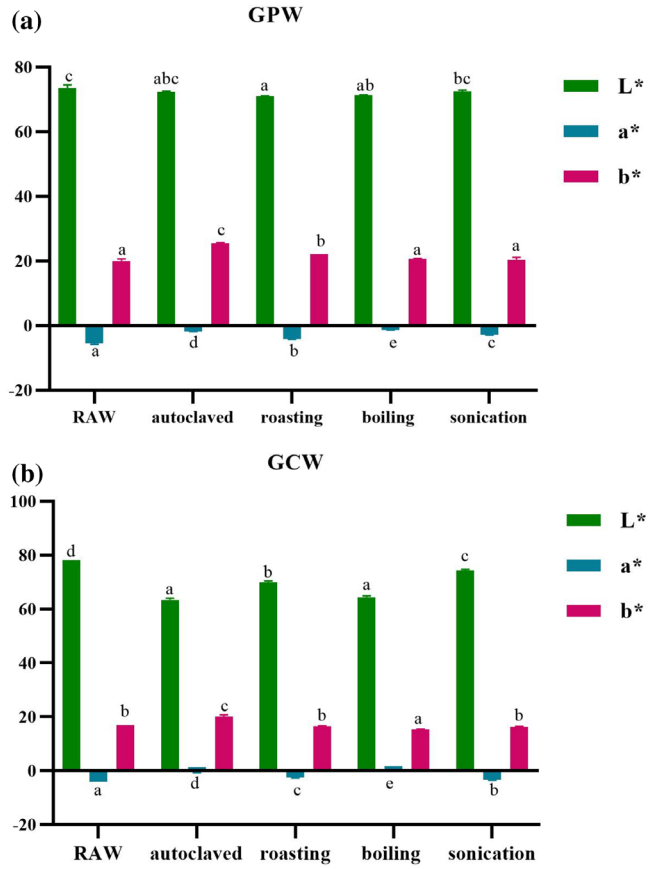



**FIGURE 1** | (a) Cielab color value of green pea. (b) Cielab color value of green chickpea. Superscripts with different lower-case letters in the columns indicate significant differences among the mean ± SD $n = 3$ by Tukey (HSD) test ($p \leq 0.05$). GPW (green pea) and GCW (green chickpea).

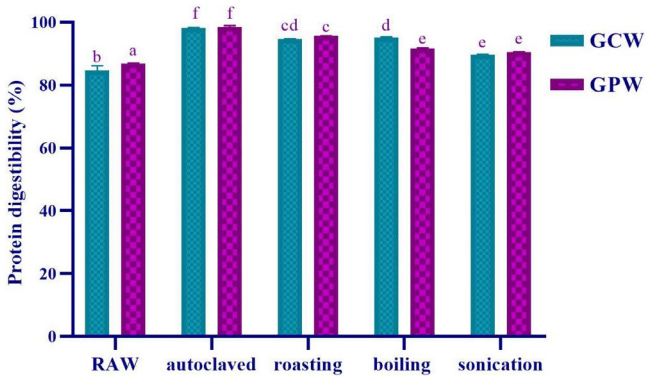



**FIGURE 2** | In vitro protein digestibility % in raw and processed green pea and green chickpea. Superscripts with different lower-case letters in the columns indicate significant differences among the mean ± SD $n = 3$ by Tukey (HSD) test ($p \leq 0.05$). GPW (green pea) and GCW (green chickpea).

### 3.7 | Bioavailability of Antioxidant During In Vitro Digestibility

The antioxidant activity increased substantially in autoclaved samples and remained comparatively stable in roasted samples as digestion progressed. Figure S1a,b showed the increasing trend of antioxidant activity. During simulated digestion, the intestinal membrane phase exhibited the highest antioxidant activity. In this phase, the $IC_{50}$ value for DPPH radical scavenging increased by 1.5-fold in green pea flour (GPW) and 1.2-fold in green chickpea flour (GCW) compared to their respective raw forms, indicating enhanced antioxidant potential. Similarly, ABTS radical scavenging activity showed a significant increase in autoclaved samples, with GPW demonstrating a 2.2-fold rise and GCW a 1.8-fold increase relative to untreated controls. These findings suggest that thermal processing methods—such as boiling, roasting, and autoclaving—can substantially influence the bioavailability of phenolic compounds. The type and intensity of heat treatment affect the release and accessibility of antioxidants, thereby modulating their absorption and efficacy within the digestive system. The cause of this might be short-chain peptides providing electrons to free radicals to stop the radical chain reaction, turning them into more stable molecules by Aluko (2015).

### 3.8 | Free Amino Acid Composition

Tables 6 and 7 present the free amino acid composition of both green pea and green chickpea. Non-essential amino acid aspartic acid content was high in GPW raw (11.03 mg/100 g) and GCW raw (11.23 mg/100 g). Essential amino acid leucine, lysine, and methionine content increased after processing treatment, roasting and boiling in GPW roasting (7.26, 6.51, 1.85 mg/100 g) and GCW roasting (5.98, 5.50, 1.77 mg/100 g). In high processing treatments, a decrease was observed in autoclave and sonication. Sulfur-containing amino acids cysteine and methionine are considered limiting amino acids in legumes. Similar results were reported by Koivunen et al. (2016) and Siddhuraju and Becker (2005).

### 3.9 | Free Fatty Acid Composition Analysis

Figure S2 depicts the composition of major fatty acids in green pea and green chickpea, obtained unsaturated fatty acids linoleic, linolenic, myristic, palmitic, stearic, and oleic acid. After sonication treatment, linoleic acid and myristic acid were detected highest among other processing techniques in green chickpea (775 and 548 mg/100 g); whereas, in green pea, linoleic, linolenic, and myristic acids were found highest in GPW raw (661.88, 550.57, 441.99 mg/100 g). Consistent results were reported (Padhi et al. 2017). Considering it reduces the risk factors linked to cardiovascular illnesses, this unique fatty acid composition is good for human health. Processing treatments, autoclaving, roasting, and boiling, decrease the fatty acid content due to oxidation during heat, migration into cooking water, or degradation at high temperature (Pirman and Stibilj 2003).

## 4 | Conclusion

This study explores the effects of four different sustainable processing techniques: autoclaving, roasting, boiling, and sonication, which were employed to enhance the nutritional, functional, and bioactive properties of green pea and green chickpea flour. Among all four techniques, autoclaving and

**TABLE 6** | Determination of free amino acids of green pea (mg/100 g) of sample.

| Amino acids | GPW (raw) | GPW (autoclave) | GPW (roasting) | GPW (boiling) | GPW (sonication) |
|---|---|---|---|---|---|
| Methionine* | $1.32 \pm 0.45^{a}$ | $0.88 \pm 0.22^{ab}$ | $1.85 \pm 0.57^{ab}$ | $1.71 \pm 0.86^{a}$ | $0.91 \pm 0.46^{ab}$ |
| Cysteine | $1.77 \pm 0.91^{ab}$ | $0.76 \pm 0.44^{a}$ | $1.10 \pm 0.23^{a}$ | $0.90 \pm 0.13^{a}$ | $0.63 \pm 0.19^{a}$ |
| Lysine* | $4.33 \pm 0.32^{e}$ | $2.11 \pm 0.47^{abc}$ | $6.51 \pm 0.39^{fg}$ | $5.11 \pm 0.40^{c}$ | $3.11 \pm 0.45^{e}$ |
| Arginine* | $8.01 \pm 0.07^{g}$ | $3.97 \pm 0.22^{e}$ | $7.71 \pm 0.19^{h}$ | $6.20 \pm 0.31^{d}$ | $4.93 \pm 0.49^{g}$ |
| Tyrosine | $2.73 \pm 0.27^{bc}$ | $1.22 \pm 0.39^{ab}$ | $4.10 \pm 0.52^{c}$ | $3.73 \pm 0.18^{b}$ | $2.20 \pm 0.02^{cde}$ |
| Phenylalanine* | $5.55 \pm 0.59^{f}$ | $3.79 \pm 0.90^{de}$ | $6.89 \pm 0.57^{gh}$ | $7.11 \pm 0.29^{d}$ | $3.79 \pm 0.23^{f}$ |
| Aspartic acid | $11.03 \pm 0.28^{h}$ | $7.76 \pm 1.04^{f}$ | $10.25 \pm 0.40^{i}$ | $9.01 \pm 0.27^{e}$ | $6.91 \pm 0.44^{h}$ |
| Proline | $4.22 \pm 0.11^{de}$ | $2.31 \pm 0.19^{bcd}$ | $5.66 \pm 0.31^{ef}$ | $3.98 \pm 0.30^{b}$ | $2.93 \pm 0.15^{def}$ |
| Glycine | $4.19 \pm 0.25^{de}$ | $2.36 \pm 0.43^{bcd}$ | $4.51 \pm 0.43^{cde}$ | $4.01 \pm 0.15^{b}$ | $1.79 \pm 0.11^{bc}$ |
| Alanine | $4.01 \pm 0.09^{de}$ | $2.01 \pm 0.55^{abc}$ | $4.42 \pm 0.24^{cd}$ | $4.11 \pm 0.53^{bc}$ | $1.68 \pm 0.52^{bc}$ |
| Isoleucine* | $5.13 \pm 0.25^{ef}$ | $2.93 \pm 0.28^{cde}$ | $5.55 \pm 0.34^{def}$ | $4.78 \pm 0.05^{bc}$ | $2.02 \pm 0.14^{cd}$ |
| Leucine* | $4.09 \pm 0.18^{de}$ | $2.19 \pm 0.32^{abc}$ | $7.26 \pm 0.38^{gh}$ | $5.10 \pm 0.14^{c}$ | $3.27 \pm 0.31^{f}$ |
| Histidine* | $3.11 \pm 0.22^{cd}$ | $0.98 \pm 0.14^{ab}$ | $2.56 \pm 0.20^{b}$ | $1.71 \pm 0.12^{a}$ | $0.69 \pm 0.16^{a}$ |

*Note:* Resulted values are expressed as mean ±SD values and *indicates the Essential Amino acids. Data in the same column with the different lower case letters are significantly different at ($p < 0.05$.) by Tukey (HSD) test.

**TABLE 7** | Determination of free amino acids of green chickpea (mg/100 g) of sample.

| Amino acids | GCW (raw) | GCW (autoclave) | GCW (roasting) | GCW (boiling) | GCW (sonication) |
|---|---|---|---|---|---|
| Methionine* | $1.33 \pm 0.14^{a}$ | $1.22 \pm 0.04^{a}$ | $1.77 \pm 0.41^{ab}$ | $1.10 \pm 0.23^{ab}$ | $1.51 \pm 0.52^{a}$ |
| Cystine | $1.71 \pm 0.02^{ab}$ | $1.03 \pm 0.08^{a}$ | $0.99 \pm 0.13^{a}$ | $0.77 \pm 0.46^{a}$ | $1.84 \pm 0.38^{a}$ |
| Lysine* | $4.49 \pm 0.31^{de}$ | $3.33 \pm 0.23^{cd}$ | $5.50 \pm 0.32^{de}$ | $3.83 \pm 0.50^{ef}$ | $5.92 \pm 0.09^{cd}$ |
| Arginine* | $8.88 \pm 0.51^{g}$ | $4.91 \pm 0.03^{e}$ | $6.67 \pm 0.29^{ef}$ | $4.99 \pm 0.05^{f}$ | $9.10 \pm 0.21^{f}$ |
| Tyrosine | $2.23 \pm 0.50^{bc}$ | $1.42 \pm 0.17^{a}$ | $3.39 \pm 0.35$ | $3.01 \pm 0.19^{cde}$ | $3.59 \pm 0.29^{b}$ |
| Phenylalanine* | $6.72 \pm 0.06^{f}$ | $3.80 \pm 0.18^{d}$ | $7.87 \pm 0.10^{fg}$ | $4.79 \pm 0.84^{f}$ | $7.19 \pm 0.25^{e}$ |
| Aspartic acid | $11.23 \pm 0.07^{h}$ | $8.11 \pm 0.14^{f}$ | $9.19 \pm 0.2^{g}$ | $7.76 \pm 0.22^{g}$ | $12.46 \pm 0.47^{g}$ |
| Proline | $4.01 \pm 0.49^{d}$ | $2.71 \pm 0.26^{b}$ | $4.44 \pm 0.27^{cd}$ | $2.81 \pm 0.20^{cde}$ | $4.99 \pm 0.26^{3}$ |
| Glycine | $4.77 \pm 0.54^{de}$ | $2.93 \pm 0.05^{bc}$ | $3.59 \pm 0.39^{c}$ | $2.01 \pm 0.63^{abc}$ | $5.12 \pm 0.35^{c}$ |
| Alanine | $4.12 \pm 0.21^{d}$ | $2.88 \pm 0.15^{b}$ | $3.11 \pm 1.16^{bc}$ | $2.36 \pm 0.47^{bcd}$ | $5.88 \pm 0.36^{cd}$ |
| Isoleucine* | $5.10 \pm 0.31^{e}$ | $3.01 \pm 0.23^{bc}$ | $4.11 \pm 0.18^{cd}$ | $2.91 \pm 0.28^{cde}$ | $6.23 \pm 0.41^{de}$ |
| Leucine* | $4.47 \pm 0.01^{de}$ | $3.22 \pm 0.33^{bc}$ | $5.98 \pm 0.95^{e}$ | $3.78 \pm 0.86^{def}$ | $5.36 \pm 0.47^{cd}$ |
| Histidine* | $3.01 \pm 0.27^{c}$ | $1.01 \pm 0.09^{a}$ | $1.92 \pm 0.03^{ab}$ | $0.93 \pm 0.60^{ab}$ | $3.36 \pm 0.36^{b}$ |

*Note:* Resulted values are expressed as mean ±SD values and *indicates the Essential Amino acids. Data in the same column with the different lower case letters are significantly different at ($p < 0.05$.) by Tukey (HSD) test.

roasting significantly impacted the nutritional content, bioactive compounds, and color parameters in green pea and green chickpea. Both processing methods significantly enhanced the nutritional profile, particularly by increasing carotenoids and dietary fiber. Additionally, a reduction in phytic acid was observed, which may enhance mineral bioavailability by mitigating its inhibitory effects on mineral absorption. HPLC analysis revealed elevated levels of both free and bound phenolic compounds following processing, indicating a substantial improvement in antioxidant capacity. These findings emphasize the potential health benefits associated with processed legumes. Color analysis showed a noticeable change in the visual appearance, characterized by an increase in $b^*(+)$ in yellowness and $a^*(-)$ decrease in greenness and $L^*$ lightness, indicating chemical transformations induced by thermal and mechanical processing treatments. Furthermore, the simulated digestion process showed that antioxidants in both peas and chickpeas became more bioavailable after autoclaving and roasting. Antioxidant bioavailability increased by up to 2.2 times in peas and 1.8 times in chickpeas. These results

highlight the efficacy of sustainable processing methods in improving the nutritional and functional quality of legume-based flours. Overall, autoclaving and roasting improve the nutritional value and antioxidant bioavailability of legumes, making them more beneficial for health. These findings could aid in developing functional foods that utilize legumes as a source of bioactive compounds and antioxidants in the future.

### Author Contributions

**Pallavi Phian:** methodology, investigation, software, writing original draft, writing – review and editing. **Mahesh Gupta:** conceptualization, methodology, supervision, writing – review and editing.


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### Ethics Statement

The work reported in this paper does not involve any studies related to humans or animals.

### Conflicts of Interest

The authors declare no conflicts of interest.

### Data Availability Statement

Data will be made available on request.

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**Supporting Information**

Additional supporting information can be found online in the Supporting Information section. **Figure S1:** (a) DPPH radical scavenging activity of in vitro digestibility. (b) ABTS radical scavenging activity of in vitro digestibility. **Figure S2:** Free fatty acid profiling of raw and processed green pea and green chickpea.