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Vol. 24(2)

May-August, 2026

CONTENTS

- AI and geospatial innovations for Indian agriculture: Applications, policy support and emerging research frontiers (Review)** 233-247
ABHISHEK DANODIA, SURESH KUMAR and AJEET SINGH NAIN
- Optimizing nitrogen use efficiency and grain quality in basmati rice through Integrated weed management: Insights into nutrient partitioning and Crop-weed competition** 248-255
ROMAN NISSAR, MANZOOR A GANAI, MEHRAJ UD DIN SOFI, ASHAQ HUSSAIN and F. A. BAHAR
- Performance evaluation of brown top millet (*Brachiaria ramosa* L.) genotypes under rainfed upland ecology of the Bastar plateau of Chhattisgarh** 256-266
PRAFULL KUMAR
- Effect of pre-harvest sprays of nanofertilizers on fruit quality in litchi (*Litchi chinensis* Sonn.) cv. Rose Scented** 267-274
NITIN PANWAR, RATNA RAI and RAJEEW KUMAR
- Ethrel induced ripening optimally modulates physicochemical quality, antioxidant properties and shelf life of sapota (*Manilkara zapota* L.) cv. Cricket Ball** 275-285
ASHOK KUMAR SINGH, KIRTI CHETRI, RISHABH RAJ, S. K. GURU and N. C. SHAHI
- Influence of drip irrigation and mulching practices on fruit set, yield and water use efficiency of litchi cv. rose scented in the Tarai region of Uttarakhand** 286-292
SHANKAR LAL, N. SINGH, N.K. BIND, PRERNA PRACHI, RAJSHREE, RIYA THAPA and AKHIL RUHELA
- Spatial distribution and survey of soybean anthracnose in the Kumaon region of Uttarakhand, India** 293-300
MANISHA DEV and K.P. SINGH
- Dimensionality reduction of part milk yield in crossbred cattle using Principal Component Analysis** 301-307
SIMRAN KAUR, ASHIS KUMAR GHOSH, OLYMPICA SARMA and RAVINDER SINGH BARWAL
- Comparative histomorphological and histochemical studies on the abomasum of adult Bakerwali goats, non-descript goats and non-descript sheep of the Jammu region** 308-318
JASVINDER SINGH SASAN, SHALINI SURI and KAMAL SARMA
- Gross morphology and biometry on the abomasum of adult Bakerwali goat, non-descript goats and non-descript sheep of Jammu region: A comparative study** 319-325
JASVINDER SINGH SASAN, SHALINI SURI and KAMAL SARMA

Arterial blood gas analysis in bovine pneumonia: Comparative study of healthy and diseased cattle ASMITA NARANG and CHARANJIT SINGH	326-331
Assessment of commonly used insecticide residues using gas chromatography in buffalo liver samples collected from North India S. K. JAIN, VINOD KUMAR, VINAY KANT, PREETI BAGRI, ARCHANA LOHIYA, GAURI CHANDRATRE and GAURAV GUPTA	332-339
<i>In silico</i> molecular docking analysis of squalene with major ageing-related molecular targets: matrix metalloproteinase-1, matrix metalloproteinase-9, cyclooxygenase-2, Tumor Necrosis Factor-α, hyaluronidase-1 and B-cell lymphoma-2 PAWANESH TAMTA, KULDIP CHANDRA VERMA and APARNA DIXIT	340-352
Characterization of agro-waste (<i>Parthenium hysterophorus</i>) derived Carbon Dots and to assess their potential as a sustainable adsorbent NISHTHA NAUDIYAL and R.K. SRIVASTAVA	353-360
Assessment of the antibacterial efficacy of endophytic bacteria in combination with neem leaf powder against bacterial pathogens SHIVANI SINGH, AJAY VEER SINGH and VELLAICHAMY MAGESHWARAN	361-370
Exploration of endophytic bacterial isolates from Kasni leaves (<i>Cichorium intybus</i>) for Phyto-hormone and Phyto-stimulating metabolite production VARSHA MISHRA, SEEMA BISHT, DIVYA PANT, ANUPAMA PANDEY and LAKSHMI TEWARI	371-382
Mitigation of dexamethasone-induced cardiac oxidative damage by <i>Moringa oleifera</i> and Vitamin E-Selenium: A biochemical study in broilers LATA PALIWAL, SONU AMBWANI and TANUJ KUMAR AMBWANI	383-395
Adaptive Neural Networks for dynamic prioritization in autonomous vehicles for road users MUMUKSHU BHATT, SUBODH PRASAD, RAJESH SINGH, ASHOK KUMAR and POOJA TAMTA	396-403
Assessing the impact of Geopolitical Disturbances on India's agricultural trade performance JYOTI, SUMAN GHALAWAT, MEGHA GOYAL, SUNIL KUMAR, AMITA GIRDHAR and SUBODH AGARWAL	404-409
Black soybean (<i>Glycine max</i> (L.) Merrill): Nutritional and functional analysis of whole seed, dehusked seed and husk fractions RITA SINGH RAGHUVANSHI, GUNJAN TEWARI, AABHA RAWAT and APURVA	410-421
<i>In silico</i> bioprospecting of bioactive phytochemicals with potential protective effects against exercise-induced muscle stiffness NAGARJUN G. S., PAL MURUGAN M., KRISHNANDU MONDAL, PADMASHREE A., WADIKAR D. D. and KUMAR R.	422-433

Black soybean (*Glycine max* (L.) Merrill): Nutritional and functional analysis of whole seed, dehusked seed and husk fractions

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ABSTRACT: Black soybean (*Glycine max* (L.) Merrill) is widely recognized for its rich nutritional composition, antioxidant properties, and potential role in the management of metabolic disorders. The present study was undertaken to evaluate the nutritional and functional characteristics of black soybean by comparing whole seeds, dehusked cotyledons, and husk fractions. Proximate composition, mineral content, dietary fibre, antioxidant activity and antinutritional factors were analysed using standard analytical methods, and the glycaemic index of whole and dehusked fractions was determined. The results revealed that dehusked cotyledons contained the highest protein content (36.94 g/100 g) and were rich in essential minerals, whereas the husk fraction exhibited the highest dietary fibre content (68.75 g/100 g) along with greater antioxidant activity. Antinutritional factors such as phytic acid and tannins were predominantly present in the husk fraction but remained within safe limits. Both whole and dehusked fractions showed low glycaemic index values (17.69±0.52 and 23.3±0.68, respectively). The findings indicated that different fractions of black soybean possess significant nutritional potential, and the underutilised husk can be effectively utilised in the development of fibre-rich functional foods.

Keywords: Antinutritional factors, Antioxidants, Black soybean, Glycaemic Index, Proximate Composition, Seed Husk

Black soybean (*Glycine max* (L.) Merrill), belonging to the family Fabaceae and subgenus *Soja* of the genus *Glycine*, has been traditionally consumed for centuries in various Asian countries, including China, Japan, Korea, Indonesia and India (Bhartiya *et al.*, 2020). However, with the increasing cultivation of yellow soybean varieties primarily for oil extraction, the traditional dietary use of black soybean has gradually declined.

Soybean is globally recognized for its significant role in food and nutritional security, serving as an excellent source of plant-based protein, essential fatty acids, dietary fibre, and bioactive compounds. Among its various types, black soybean has gained considerable attention due to its rich composition of polyphenols, anthocyanins, and other phytochemicals, predominantly concentrated in the seed coat (Kumar *et al.*, 2023; Li *et al.*, 2024). Its dense micronutrient profile makes it a promising dietary component for addressing hidden hunger and improving nutritional outcomes, particularly in populations affected by food insecurity and related

challenges (Singh and Krishnaswamy, 2022).

In India, black soybean, commonly known as *Kala Bhatt*, holds cultural and traditional importance, especially in hilly regions. Despite its recognized nutritional value, its utilization in modern food systems remains limited. Conventionally, black soybean is consumed as whole seeds or dehusked cotyledons. At the same time, the husk is generally removed and discarded as a by-product, even though it is a rich source of dietary fibre and bioactive compounds.

Given the growing consumer demand for fibre-rich and functional foods, the present study aimed to evaluate the nutritional and functional characteristics of black soybean by analysing whole seeds, dehusked cotyledons, and husk fractions for proximate composition, mineral content, dietary fibre, antioxidant activity, and antinutritional factors. Additionally, the glycaemic index of whole and dehusked fractions was assessed to determine their potential role in managing metabolic disorders.

MATERIALS AND METHODS

Procurement of Raw Material

Black soybean (*Glycine max* (L.) Merrill) used in this study was procured from Majhera Research Centre, Bhimtal, G.B. Pant University of Agriculture and Technology, Pantnagar, Uttarakhand.

Processing of Black Soybean

The procured black soybean was cleaned to remove dust and foreign matter. Dehusking was performed using a mini dal mill to obtain dehusked soybean and husk separately. Whole, dehusked, and husk fractions were ground in an electric grinder, passed through a sieve for uniform particle size, and stored in airtight containers for analysis.

Proximate Composition

Moisture, ash, crude protein, crude fat, crude fiber, and carbohydrate content were analyzed following the methods of Association of Official Analytical Chemists (1995). Carbohydrate was determined by difference. All proximate analyses were performed in triplicate ($n = 3$) for each sample.

Mineral Composition

Calcium, iron, zinc, and magnesium contents were determined using Sens AA dual atomic absorption spectrophotometer (GBC Scientific Equipment). Mineral analysis was carried out after wet digestion of the samples using a tri-acid mixture of nitric acid (HNO_3), perchloric acid (HClO_4), and sulphuric acid (H_2SO_4) in the ratio of 3:2:1. Digestion was performed at 120–150°C until a clear solution was obtained and dense fumes ceased. The digested samples were cooled, filtered, and diluted to a known final volume with double-distilled water before analysis. Blank determination was carried out simultaneously for all mineral estimations.

Calibration curves for calcium, iron, zinc, and magnesium were prepared using certified analytical grade standard solutions of each mineral.

The atomic absorption spectrophotometer was operated at the following wavelengths: calcium (422.7 nm), iron (248.3 nm), zinc (213.9 nm), and

magnesium (285.2 nm). Concentrations of minerals in the samples were determined by comparing absorbance values with standard calibration curves.

Antinutritional Factors

Phytic acid was determined by the method of Wheeler and Ferrel (1971), tannins by the Folin-Denis method (Association of Official Analytical Chemists, 1970), oxalates by Baker (1952), and trypsin inhibitor activity by Liu and Markakis (1989).

Antioxidant Activity

Antioxidant compounds were extracted from soybean flour using 85% aqueous methanol at a solid-to-solvent ratio of 1:10 (w/v). The mixture was stirred continuously for 30 min at room temperature and then centrifuged at 2500 rpm for 10 min. The supernatant was collected and used as crude extract for further analysis.

Total phenolic content was estimated using Folin–Ciocalteu reagent (Singleton *et al.*, 1999). The results were expressed as mg gallic acid equivalent (GAE)/100 g using a gallic acid calibration curve. Total flavonoid content was determined according to Zhishen *et al.* (1999) and expressed as mg rutin equivalent (RE)/100 g using rutin standard curve.

DPPH radical scavenging activity was measured using 0.1 mM DPPH solution prepared in methanol (Brand-Williams *et al.*, 1995). Briefly, an aliquot of extract was reacted with DPPH solution and incubated in the dark at 37°C for 20 min. The absorbance was measured at 517 nm using a UV–Visible spectrophotometer. Antioxidant activity was expressed as percentage inhibition of DPPH radical using standard equation.

DPPH radical scavenging activity (%) = $\frac{[(\text{Absorbance of control} - \text{Absorbance of sample}) / \text{Absorbance of control}] \times 100}{1}$

Dietary Fibre

Total dietary fiber was estimated by the standard method where samples were gelatinized, enzymatically digested to remove protein and starch,

and filtered to obtain insoluble fiber. Soluble dietary fiber was precipitated from the filtrate and determined gravimetrically (Asp *et al.*, 1983).

Glycaemic Index

The glycaemic index (GI) of black soybean (both whole and dehusked) was determined through a human study involving ten healthy female volunteers aged 22 to 24 years. Participation was based on informed consent, and ethical approval was obtained from the University Ethics Committee for Human Research (UECHR) vide letter no. CHS131.

Subjects were instructed to maintain their habitual diet and undergo an overnight fast of 10–12 hours before each test session. A 25 g anhydrous glucose solution (in 100 mL water) was used as the reference food (GI = 100). Test portions of whole and dehusked soybeans were provided on alternate days, each containing 25 g available carbohydrates.

Capillary blood glucose was measured using the finger-prick method at 0, 15, 30, 45, 60, 90, and 120 min using a calibrated glucometer (Bayer Contour). Incremental area under the blood glucose curve (IAUC) was calculated using the trapezoidal rule, ignoring values below baseline. Glycaemic index was calculated as:

$$GI = \left(\frac{\text{Incremental Area Under the Curve (IAUC) of test food}}{\text{Incremental Area Under the Curve (IAUC) of reference glucose}} \right) \times 100$$

Statistical Analysis

Data were analyzed by one-way ANOVA using MS-Excel as described by Snedecor and Cochran (1980). All analyses were performed in triplicate. The results were expressed as mean $\pm$ standard deviation (SD), and differences among the samples were considered significant at $p < 0.05$.

RESULTS AND DISCUSSION

Proximate Composition

The proximate composition of black soybean in whole, dehusked, and husk fractions is presented in Table 1. Whole seeds contained $38.92 \pm 0.88\%$ protein and $23.01 \pm 0.20\%$ fat, while dehusked seeds retained slightly lower protein ($36.94 \pm 0.74\%$) and

slightly higher fat content i.e., $24.23 \pm 0.45\%$. The husk fraction was notably rich in crude fiber ($43.77 \pm 0.21\%$) and carbohydrates ($36.5 \pm 2\%$). Ash content ranged from $4.78 \pm 0.05\%$ in the husk to $6.28 \pm 0.23\%$ in whole seeds. Physiological energy was highest in the dehusked fraction (474 ± 4.04 kcal/100g) and lowest in the husk (207 ± 3.12 kcal/100g).

Mineral Composition

The mineral content of black soybean is summarized in Table 2. Whole seeds contained 13.32 ± 0.44 mg/100g iron, 5.37 ± 0.34 mg/100g zinc, 226.66 ± 5.57 mg/100g magnesium, and 387.13 ± 2.97 mg/100g calcium. Dehusking led to slight reductions in mineral content, whereas the husk fraction consistently showed the highest mineral concentrations with 16.13 ± 0.35 mg/100g iron, 5.98 ± 0.05 mg/100g zinc, 288.56 ± 2.93 mg/100g magnesium, and 495.35 ± 2.93 mg/100g calcium.

Antinutritional Factors

Antinutritional components of black soybean are shown in Table 3. Tannin and trypsin inhibitor concentrations were highest in the husk ($6.47 \pm 0.30\%$ and 4.56 ± 0.05 mg/g respectively) whereas phytic acid and oxalates were moderately distributed across fractions. Whole and dehusked seeds showed lower levels of tannins and trypsin inhibitors.

Antioxidant Activity of Black Soybean

Antioxidant properties including total phenols, total flavonoids and DPPH radical scavenging activity are summarized in Table 4. The husk fraction exhibited the highest antioxidant activity 3467.68 ± 14.9 mg GAE/100 g phenols, 9950 ± 53.03 mg RE/100 g flavonoids and $62.46 \pm 0.36\%$ DPPH scavenging whereas dehusked seeds had the lowest values. Whole seeds showed intermediate activity.

Dietary Fiber

The dietary fiber content of black soybean is presented in Table 5. The husk fraction contributed the majority of fiber, with 76% insoluble dietary fiber (IDF), 3.66% soluble dietary fiber (SDF), and 79.51% total dietary fiber (TDF). Whole seeds contained 42.13% TDF (39.16% IDF and 2.83% SDF) while dehusked seeds retained 34.38% TDF

(31.81% IDF and 2.57% SDF).

Glycaemic Index

Black soybean exhibited a low glycaemic index (GI). Whole seeds had a GI of 17.69 ± 0.52 , whereas dehusked seeds showed a slightly higher GI of 23.3 ± 0.68 , indicating a slow and sustained glucose release.

DISCUSSION

Proximate composition

The proximate composition of whole, dehusked, and husk fractions of black soybean demonstrates its remarkable nutritional density, establishing it as a promising candidate for dietary interventions targeting protein-energy malnutrition (PEM) and hidden hunger. The ash content of black soybean (6.28 ± 0.23 g/100 g) reflects its high mineral density, contributing significantly to calcium, magnesium, phosphorus, and trace element intake. By comparison, yellow soybean contains $5.27 \pm 1.32\%$ ash (Oli *et al.*, 2024), while other legumes such as lentils and chickpeas range from 2–3 per cent (Longvah *et al.*, 2017). This mineral richness underscores the potential of black soybean in addressing micronutrient deficiencies, a major component of hidden hunger.

Whole black soybean is a substantial source of crude

fiber ($8.38 \pm 0.08\%$), and dehusked seeds retain a notable level ($4.98 \pm 0.05\%$), indicating that even without the husk black soybean remains a good source of dietary fiber. The husk fraction exhibits the highest fiber content ($43.77 \pm 0.21\%$) suggesting its suitability for formulating fiber-enriched foods aimed at improving digestion and overall metabolic health. When compared with other legumes such as dehulled green gram ($9.37 \pm 0.38\%$) and lentil dal ($10.43 \pm 0.39\%$ dietary fiber) (Longvah *et al.*, 2017), black soybean exhibits a comparable or higher dietary fiber content, highlighting its potential for supporting gut health and promoting satiety. Previous studies have also reported the superior antioxidant activity of black soybean (Chauhan *et al.*, 2022), and recent research has explored the incorporation of black soybean seed coat powder into weight-management and functional food formulations (Dhull *et al.*, 2023).

Black soybean provides a high fat content ($23.01 \pm 0.20\%$), which is essential for energy and fatty acid intake, with the dehusked fraction containing an even higher concentration ($24.23 \pm 0.45\%$). In comparison yellow soybean typically contains 13.41–19.42% fat (Moriyasu *et al.*, 2021), while other Indian pulses such as white cowpea ($1.74 \pm 0.25\%$), lentil ($2.04 \pm 0.24\%$), and rajma ($1.63 \pm 0.14\%$) (Pal *et al.*, 2020) contain

Table 1: Proximate Composition of Black Soybean (Dry Weight Basis)

Parameter	Whole	Dehusked	Husk	C.D. at 5%
Total Ash (%)	6.28 ± 0.23	5.74 ± 0.14	4.78 ± 0.05	0.33
Crude Fiber (%)	8.38 ± 0.08	4.98 ± 0.05	43.77 ± 0.21	0.28
Crude Fat (%)	23.01 ± 0.2	24.23 ± 0.45	1.75 ± 0.17	0.61
Crude Protein (%)	38.92 ± 0.88	36.94 ± 0.74	11.05 ± 0.93	1.92
Carbohydrate (%)	22.7 ± 0.86	27.23 ± 0.79	36.5 ± 2	2.68
Physiological Energy (kcal/100g)	453 ± 2.19	474 ± 4.04	207 ± 3.12	6.42

All analyses were performed in triplicate. Critical difference (C.D.) values at 5% level of significance have been presented.

Table 2: Mineral Composition of Black Soybean (mg/100g, Dry Weight Basis)

Mineral	Whole	Dehusked	Husk	C.D. at 5%
Iron	13.32 ± 0.44	12 ± 0.4	16.13 ± 0.35	0.99
Zinc	5.37 ± 0.34	5.21 ± 0.07	5.98 ± 0.05	0.12
Magnesium	226.66 ± 5.57	209.66 ± 4.16	288.56 ± 2.93	8.83
Calcium	387.13 ± 2.97	248.44 ± 3.65	495.35 ± 2.93	6.25

All analyses were performed in triplicate. Critical difference (C.D.) values at 5% level of significance have been presented.

substantially less. The elevated fat content of black soybean contributes to its physiological energy value, making it suitable for energy-dense therapeutic foods (Mitharwal *et al.*, 2024).

The crude protein content of whole black soybean is exceptionally high ($38.92 \pm 0.88\%$), nearly twice that of commonly consumed Indian pulses such as chickpea ($19.61 \pm 2.61\%$) and lentil ($20.43 \pm 2.55\%$) (Pal *et al.*, 2020). It slightly surpasses yellow soybean, which contains 37.80% protein according to the Indian Food Composition Tables (Longvah *et al.*, 2017). This positions black soybean as one of the most potent sources of plant protein. Considering the persistent issue of PEM in India, where 35.5% of children under five are stunted and 13.7% of the overall population is undernourished (Concern Worldwide and Welthungerhilfe, 2024), incorporating black soybean into diets could be a valuable strategy to improve protein adequacy, particularly among vulnerable populations.

Carbohydrate content in black soybean ($22.7 \pm 0.86\%$) represents a moderate and nutritionally favorable proportion, providing sustained energy release without a high glycaemic

load. Earlier studies have reported similar carbohydrate levels in black soybean (Dobhal and Raghuvanshi, 2018). The husk fraction contains significantly higher carbohydrates ($36.5 \pm 2.0\%$), largely attributable to its non-digestible fiber components.

The caloric value of black soybean is 453 ± 2.19 kcal/100 g in whole seeds and 474 ± 4.04 kcal/100 g in dehusked seeds, with the difference being statistically significant. This energy density highlights the suitability of black soybean for inclusion in high-calorie dietary formulations, particularly for children and pregnant or lactating women, whose energy requirements are elevated.

Mineral composition

The mineral composition of black soybean observed in the present study highlights its potential as a nutrient-dense legume that can help address micronutrient deficiencies. The markedly higher mineral concentrations in the husk fraction reaffirm the seed coat's role as a primary reservoir of essential elements. This trend aligns with previous findings reporting greater accumulation of minerals such as iron, zinc, and calcium in the outer layers of legumes

Table 3: Antinutritional Factors in Black Soybean (% Dry Weight Basis)

Parameter	Whole	Dehusked	Husk	C.D. at 5%
Tannins (%)	1.65 ± 0.04	1.22 ± 0.04	6.47 ± 0.3	0.06
Phytic Acid (%)	1.18 ± 0.1	1.22 ± 0.04	0.49 ± 0.01	0.08
Oxalates (%)	0.69 ± 0.01	0.67 ± 0.04	0.18 ± 0.01	0.05
Trypsin Inhibitors(mg/g)	2.39 ± 0.03	1.52 ± 0.05	4.56 ± 0.05	0.08

All analyses were performed in triplicate. Critical difference (C.D.) values at 5% level of significance have been presented.

Table 4: Antioxidant Activity of Black Soybean

Parameter	Whole	Dehusked	Husk	C.D. at 5%
Total Phenols (mg GAE/100g)	526.73 ± 4.66	285.65 ± 5.71	3467.68 ± 14.9	19.16
Total Flavonoids (mg RE/100g)	855.95 ± 2.78	465.98 ± 2.19	9950 ± 53.03	58.09
DPPH Radical Scavenging Activity (%)	53.61 ± 1.08	28.46 ± 1.61	62.46 ± 0.36	2.33

All analyses were performed in triplicate. Critical difference (C.D.) values at 5% level of significance have been presented.

Table 5: Dietary Fiber Content of Black Soybean (% Dry Weight Basis)

Parameter	Whole	Dehusked	Husk	C.D. at 5%
Insoluble (IDF)	39.16 ± 0.32	31.81 ± 0.64	76.00 ± 0.89	1.33
Soluble (SDF)	2.83 ± 0.2	2.57 ± 0.21	3.66 ± 0.34	0.59
Total (TDF)	42.13 ± 0.24	34.38 ± 0.77	79.51 ± 1.77	1.74

All analyses were performed in triplicate. Critical difference (C.D.) values at 5% level of significance have been presented.

compared to the cotyledon (Kumar *et al.*, 2023; Li *et al.*, 2024). The decline in mineral content following dehusking underscores the nutritional loss that occurs during processing, emphasizing the importance of utilizing whole seeds or valorizing husk fractions in food formulations.

Iron, one of the most critical minerals for human health, was found in particularly high concentration in the husk (16.13 mg/100 g), highlighting its potential role in mitigating iron deficiency anaemia. Given that iron deficiency remains a widespread public health concern in India affecting 57% of women of reproductive age and 67.1% of children under five years (IIPS and ICF, 2021) the promotion of iron-rich legumes such as black soybean could have direct implications for improving dietary iron intake.

The zinc content in black soybean ranged from 5.37 ± 0.34 mg/100 g in whole seeds to 5.21 ± 0.07 mg/100 g in dehusked samples and 5.98 ± 0.05 mg/100 g in the husk. These levels are notably higher than those reported for other Indian pulses, including Bengal gram (2.6 mg/100 g), black gram (3.3 mg/100 g), and peas (2.7 mg/100 g) (Longvah *et al.*, 2017). Zinc plays an essential role in immune regulation, protein synthesis, and tissue repair, making zinc-rich foods such as black soybean valuable for supporting growth and overall health (Stiles *et al.*, 2024). Therefore, integrating black soybean into dietary programs could serve as a feasible strategy to address zinc inadequacy in predominantly vegetarian populations where cereal- and pulse-based diets are common.

Magnesium and calcium concentrations were also remarkably high, particularly in the husk fraction (288.56 mg/100 g and 495.35 mg/100 g, respectively). These findings establish black soybean as a valuable source for supporting bone health and metabolic regulation. Common pulses such as lentil, field pea, and common bean typically contain about 76–176 mg/100 g of magnesium (Sinkovič *et al.*, 2022), indicating that the magnesium content of black soybean is nearly twofold higher. Magnesium participates in over 300 enzymatic reactions,

including those regulating muscle and nerve function, glucose metabolism, and blood pressure maintenance. Similarly, calcium levels in black soybean were substantially higher than in most other commonly consumed Indian pulses, reaffirming its importance as a nutritionally rich legume. The elevated calcium concentration, especially in the husk fraction, highlights the seed coat's contribution to mineral density and its potential application in developing value-added food products. Calcium is vital for bone and dental health, neuromuscular activity, and several enzyme systems, and its adequate intake becomes increasingly important with advancing age. A large-scale Indian study involving over 31,000 adults reported osteoporosis prevalence at 18.3%, rising to more than 30% among postmenopausal women (Babhulkar and Seth, 2021). These observations collectively highlight a growing national concern regarding bone fragility and mineral loss. Therefore, inclusion of calcium-rich legumes such as black soybean in regular diets could meaningfully enhance skeletal health and reduce osteoporosis risk among vulnerable populations.

Antinutritional factor

The distribution of antinutritional factors across the whole, dehusked, and husk fractions of black soybean shows distinct variations that influence its overall nutritional quality and nutrient bioavailability. Like other legumes, black soybean contains tannins, phytic acid, oxalates, and trypsin inhibitors, whose concentrations depend largely on the fraction consumed.

Tannins were most concentrated in the husk, confirming their localization in the seed coat, consistent with earlier reports that tannins are predominantly confined to the outer layers of legumes (Pal *et al.*, 2020). Among commonly consumed pulses, black soybean husk exhibits the highest tannin concentration, whereas whole black soybean contains lower levels than lentil (5.41 g/kg) or chickpea (4.28 g/kg) (Pal *et al.*, 2020). Although excessive tannin intake can reduce protein digestibility and mineral absorption, these polyphenolic compounds also exert antioxidant, antimicrobial, and anti-inflammatory effects,

suggesting a dual role depending on intake level. Controlled inclusion of tannin-rich fractions like the husk could therefore provide functional benefits. Traditional processing methods such as roasting and fermentation significantly lower tannin content, enhancing nutrient availability (Vagadia *et al.*, 2017; Chauhan *et al.*, 2022).

Whole black soybean contained $1.18 \pm 0.10\%$ phytic acid, the dehusked fraction $1.22 \pm 0.04\%$, and the husk $0.49 \pm 0.01\%$. Compared with rajma (11.64%), horse gram (12.54%), and rice bean (13.21%) (Pal *et al.*, 2020), black soybean has markedly lower phytic acid levels, favouring better mineral absorption. However, as a chelating agent, phytic acid binds divalent minerals such as calcium, iron, and zinc, potentially reducing their bioavailability an important consideration in populations where iron-deficiency anaemia and calcium deficiency are common. At moderate levels, however, phytic acid demonstrates antioxidant and anticancer activities (Wu *et al.*, 2023; Di *et al.*, 2025)

Oxalates occurred in moderate quantities, with the lowest concentration in the husk fraction. While oxalates can hinder calcium absorption by forming insoluble calcium oxalate complexes, their levels in black soybean are substantially lower than in other pulses, indicating minimal interference with calcium bioavailability. Nonetheless, long-term consumption of high-oxalate foods may increase the risk of kidney stones or bone demineralization, highlighting the value of soaking, germination, and cooking practices to further reduce oxalate content and enhance calcium utilization.

Trypsin inhibitors, which interfere with proteolytic enzyme activity and lower protein digestibility, were higher in the husk than in whole or dehusked seeds. Even so, black soybean showed considerably lower trypsin inhibitor activity than chickpea (28.27 mg/g), cowpea (36.13 mg/g), or rajma (26.98 mg/g) (Pal *et al.*, 2020). This comparatively low activity improves its potential as a digestible protein source. Fermentation and thermal treatment effectively inactivate these inhibitors, improving protein quality and the overall nutritional profile (Vagadia *et al.*,

2017; Wu *et al.*, 2023).

Antioxidant activity

The antioxidant properties of black soybean and its fractions demonstrate a clear relationship between phenolic concentration and radical-scavenging capacity. The husk fraction exhibited the highest antioxidant potential across all parameters, confirming the seed coat as a major reservoir of bioactive phytochemicals. Consistent with these findings, earlier studies reported that the dark-pigmented seed coats of black soybeans contribute substantially to their elevated polyphenol content and strong antioxidant potential (Zhou *et al.*, 2017; Li *et al.*, 2024). The total phenolic content of the husk was several-fold higher than that of the whole and dehusked fractions, emphasizing that phenolic compounds are primarily localized in the outer layers. This agrees with previous reports noting that polyphenols in black soybean occur mainly as anthocyanins, isoflavones, phenolic acids, flavan-3-ols, and proanthocyanidins (Peng *et al.*, 2017; Soedarjo, 2019; Cabezudo *et al.*, 2021). These compounds not only impart deep pigmentation but also provide wide-ranging health benefits, including antioxidant, anti-obesity, anti-atherosclerotic, and anticancer activities (Ganesan and Xu, 2017; Yamashita *et al.*, 2020). Thus, the black soybean husk represents a valuable by-product with promising potential for nutraceutical and functional food development. The total flavonoid content followed a similar trend, with the husk exhibiting the highest concentration. Flavonoids play key roles in mitigating oxidative stress, enhancing vascular health, and protecting against cardiovascular diseases (Khan *et al.*, 2021). The abundance of anthocyanins such as cyanidin-3-monoglucoside and delphinidin-3-monoglucoside distinguishes black soybean from yellow soybean and other pulses in terms of functional food potential (Choi *et al.*, 2020; Khan *et al.*, 2021). Beyond antioxidant protection, these pigments also exert anti-inflammatory and vasoprotective effects.

The DPPH radical scavenging activity further confirmed the superior antioxidant efficacy of the husk compared to the whole and dehusked seeds,

indicating a strong link between phenolic and flavonoid levels and free radical neutralization capacity. When compared to other pulses such as rajma (27.99%), chickpea (37.44%), and lentil (49.67%) (Pal *et al.*, 2020), the black soybean husk clearly stands out for its remarkable antioxidant efficiency.

Dietary fibre

The dietary fiber composition of black soybean highlights the crucial role of the husk as the principal source of both crude and total dietary fiber. The markedly higher levels of insoluble dietary fiber (76%) and total dietary fiber (79.51%) in the husk compared with the whole and dehusked fractions underscore the localization of structural polysaccharides such as cellulose, hemicellulose, and lignin within the seed coat. Both soluble (SDF) and insoluble fiber fractions are present in black soybean (Yousif, 2014). The high insoluble fiber fraction plays an important physiological role by promoting gastrointestinal motility, increasing stool bulk, and reducing the risk of constipation and colorectal disorders (Chauhan *et al.*, 2022; Kumar *et al.*, 2023). The soluble fiber fraction, though present in smaller quantities (2.57–3.66%), contributes to cholesterol binding, lowering serum cholesterol, and moderating postprandial glycaemic response (Shen *et al.*, 2020). Structurally, black soybean soluble fiber consists mainly of pectic polysaccharides such as homogalacturonan and rhamnogalacturonan I, and hemicelluloses including arabinoxylan, xyloglucan, and galactomannan the latter being particularly abundant (Wu *et al.*, 2023). These characteristics enhance water-holding capacity, fermentability, and the growth of beneficial gut microbiota, thereby promoting colonic health and short-chain fatty acid production (Pramitasari *et al.*, 2021; Wu *et al.*, 2023).

Compared with other Indian pulses, black soybean demonstrates a superior fiber profile. Lentils contain about 10.7 g/100 g total dietary fiber (USDA, 2018), while chickpea and kidney beans provide approximately 11–15% (Pal *et al.*, 2020). This higher fiber density positions black soybean as a promising food for increasing dietary fiber intake and lowering

the risk of non-communicable diseases associated with low-fiber diets.

Recent experimental and product development studies further support the functional potential of black soybean fiber. Supplementation with black soybean seed coat powder has been shown to reduce body weight gain and improve adipocytokine profiles in high-fat diet-induced obese mice, outperforming yellow soybean counterparts (Dhull *et al.*, 2023). Likewise, incorporation of black bean hulls into nixtamalized maize tostadas increased protein, fiber, and anthocyanin content while reducing the predicted glycaemic index, demonstrating synergistic benefits for metabolic health (Machado-Velarde *et al.*, 2023). Processing treatments such as fermentation and germination further enhance fiber bioavailability and functional efficacy (Chauhan *et al.*, 2022).

Glycaemic index

The glycaemic index (GI) of black soybean observed in the present study was 17.69 in whole and 23.3 in dehusked, placing it well within the low-GI category ($GI \leq 55$), which is associated with slower digestion, gradual glucose release and reduced postprandial glycaemic response (Atkinson *et al.*, 2021). Jenkins *et al.* (1981) reported a GI value of approximately 15 for boiled soybeans, while Foster-Powell *et al.* (2002) documented a mean GI value of 18 for boiled soybeans in the international glycaemic index tables. The close similarity of these published values with the present result supports the validity of the observed GI, particularly since black soybean is a variety of *Glycine max*.

The very low GI of black soybean may be attributed to the synergistic effects of its high protein, dietary fibre, lipid, and resistant starch contents, which reduce gastric emptying, delay carbohydrate digestion, and slow intestinal glucose absorption. In addition, bioactive compounds such as polyphenols, isoflavones, and anthocyanins may further improve glucose metabolism and insulin sensitivity by modulating pathways involved in glucose uptake and carbohydrate metabolism (Kumar *et al.*, 2023; Li *et al.*, 2024).

Oligosaccharides such as stachyose and raffinose may also contribute to glucose homeostasis through gut microbiota modulation and enhanced short-chain fatty acid production (Machado-Velarde *et al.*, 2023). Clinical evidence further supports these observations, as black soybean supplementation has been associated with improvements in fasting blood glucose and metabolic parameters (Pi *et al.*, 2024). Thus, the low GI value obtained in the present study is scientifically justified and reinforces the potential of black soybean as a functional ingredient for diabetic-friendly foods and metabolic health management.

CONCLUSION

This study aimed to comprehensively evaluate the nutritional composition, glycaemic index, antioxidant activity, and antinutritional factors of black soybean across whole, dehusked, and husk fractions, and the findings confirm that whole black soybean is a valuable source of protein, fat, minerals, antioxidants, and dietary fiber, in a vegetarian diet. The husk fraction, although low in protein and fat, exhibited exceptionally high dietary fiber and phenolic content, indicating its potential use as a functional ingredient. Incorporating the husk into food products or nutraceuticals will not only enhance nutritional value but also promote waste valorization, contributing to more sustainable food systems. The parameters analysed highlight black soybean's potential for use in therapeutic foods aimed at managing diabetes, dyslipidaemia, and obesity. Overall, the study reaffirms black soybean as a nutrient-dense legume with multifaceted applications, supporting sustainable food systems through comprehensive utilization of all its parts. Further research focusing on bioavailability, sensory acceptability, and clinical validation of its health-promoting effects would strengthen its role as a functional ingredient in human nutrition.

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