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Sustainable valorization perspective of legume hulls to enhance the nutritional and functional properties of pasta

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Legume hulls, often considered byproducts, are sustainable sources of phenolics and minerals. Their utilisation targets the sustainable development goals by reducing waste and improving the nutritional value of conventional foods. In the present study, pasta was prepared by replacing semolina with legume (chickpea, black gram, and moong bean) hulls at 10%, 20%, and 30% levels. Hull incorporation significantly ($p < 0.05$) influenced the cooking quality, increasing the minimum cooking time (11.3–14.3 min), water absorption (121–157%), volume expansion (up to 233%), and gruel solid loss (up to 5.31%), with more pronounced effects observed at higher substitution levels. Sensory evaluation also revealed significant changes in the acceptability upon an increase in hull incorporation levels. Principal component analysis concluded that pasta containing 20% legume hulls achieved the optimum balance in cooking and organoleptic qualities; therefore, these samples were further analysed for their nutritional and technofunctional properties. The incorporation of legume hulls resulted in increased ash, fat, and fibre contents; however, the carbohydrate content decreased. The amino acid profile revealed an enhancement in the lysine, tyrosine, tryptophan, valine, leucine, and threonine contents in hull-incorporated pasta, while *in vitro* protein digestibility showed minor variation. Moreover, hull incorporation modulated the mineral and phenolic profiles; notably, black gram hull pasta showed an enrichment of catechin, syringic acid, and coumaric acid. The pasting profile revealed reduced peak and final viscosities, while FTIR and SEM analyses demonstrated fibre-induced disruption of the starch–protein matrix while preserving the functional groups and overall structural integrity. The present study highlights the potential of legume hulls as sustainable functional ingredients, supporting circular bioeconomy strategies while advancing the development of nutrient-dense staple foods.

Sustainability spotlight

The current study focuses on addressing the sustainable development goals of zero hunger (SDG2), good health and well-being (SDG3), responsible consumption and production (SDG12), climate action (SDG13) and life on land (SDG15) by utilizing legume processing by-products. In the present study, legume (chickpea, black gram and moong bean) hulls, considered waste products, were utilized at 10–30% levels for incorporation in pasta. The resultant product was characterized for nutritional and functional characteristics. The results depicted an enhancement in the mineral composition and phenolic profile and a considerable variation in the cooking quality, pasting and structural properties. The comprehensive exploration of legume hulls within the modern food industry highlights several prospects to advance environmental sustainability, responsible consumption, global health, and the circular economy.

1 Introduction

Edible legumes are vital to agricultural ecosystems and sustainable development.[1] They were initially cultivated as a soil conditioner, but they are now being utilized as a staple food for millions of people around the world.[2] They are essential for achieving food and nutritional security because of their low cost, high protein content, and versatility across a range of agroclimatic conditions. The demand for legume-based food products as sustainable, health-promoting substitutes has increased recently, driven by growing awareness of the environmental impact of animal-based foods and the rise in lifestyle-related problems.[3]

Legumes undergo a series of primary and secondary processing operations, including soaking, dehulling, milling, and thermal treatments, to improve their nutritional quality and functionality. Dehulling is a widely adopted postharvest

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processing technique, particularly to produce dal, legume flours, and various value-added products. While this process improves digestibility, cooking quality, and consumer acceptability, it also produces significant quantities of byproducts, primarily hulls.[4,5] From a sustainability standpoint, recycling these byproducts presents economic and ecological issues, such as waste management and resource inefficiency. Ironically, the hulls of legumes are rich in nutrients and valuable components. They are suitable for low-glycaemic-index diets because they contain low-digestible carbohydrates and oligosaccharides, and they are high in dietary fibre and bioactive substances, like phenolic acids, flavonoids, epicatechin, catechins, and resveratrol. These substances are well-known for their anti-inflammatory, antioxidant, and disease-preventive properties.[6] According to Boudjou *et al.*,[7] the hulls of faba bean seeds contain 89% flavonoids and 80% total polyphenols. Legume hulls consist of 8–10% moisture, 1–3% lipid, 2–8% protein, 3–4% ash, and 60–90% carbohydrates. The composition of different hulls varies depending on the type of legume, species, growth conditions, and processing conditions.[8,9] Hulls are made up of insoluble nonstarch polysaccharides, such as cellulose, hemicellulose, and lignin, thereby exhibiting potential as good sources of fibre for incorporation into conventional foods, including pasta, noodles, biscuits, and bread.[10]

By meeting nutritional, health, environmental, and ecological goals, the use of legume hulls is highly compatible with the Sustainable Development Goals (SDGs). The utilization of legume hulls as a functional ingredient aligns with several Sustainable Development Goals (SDGs), particularly SDG 2 (zero hunger), by improving the nutritional quality of foods and supporting food and nutrition security. Bioactive compounds and antioxidant properties also serve SDG 3 (good health and well-being), as both enhance improved health outcomes and disease prevention. Moreover, the heroization of legume hulls, which are a food processing byproduct, promotes waste minimization and responsible food production methods, in line with SDG 12 (responsible consumption and production). A food system can also achieve SDG 13 (climate action) by replacing ingredients that use resources with legume hulls (reducing the environmental footprint of the food system). Moreover, the use of agricultural byproducts in a sustainable way with respect to SDG 15 (life on land), which encourages efficient resource use and the responsible management of land, is indirectly supported.[11]

Pasta, a popular staple in many cuisines, has been the subject of dispute regarding its health consequences due to its low nutritional value and high carbohydrate content. To solve nutritional issues and answer growing consumer concerns, numerous food scientists have investigated the use of nontraditional ingredients in food.[12] Durum wheat semolina is traditionally used in the production of pasta because of its excellent functional qualities in a stable pasta formulation. However, to compensate for the nutritional deficiencies of durum wheat semolina, the use of nontraditional ingredients, such as pseudo cereals, millets, and legumes and their byproducts, has sparked considerable interest in the production of pasta.[13] According to Kaya *et al.*,[14] using lentil, pea, and faba bean hulls in Turkish noodle development improved both the nutritional quality and cooking quality of the noodles. Kanatt *et al.*[5] also observed that extracts of certain legume hulls had high phenolic contents, reducing powers, and radical scavenging activities even at very low concentrations. Costantini *et al.*[15] used a similar approach, incorporating Kabuli and Apulian black chickpea hulls into gluten-free fresh pasta, which not only increased the fibre and bioactive compound contents but also improved cooking performance and sensory quality.

The effective use of legume hulls in cereal-based products has been reported in a limited number of studies. Despite these developments, there are still few systematic studies on the use of commonly consumed Indian legume hulls, such as moong bean, black gram, and chickpea hulls, in the making of pasta. Furthermore, sufficient attention has not been paid to the combined assessment of hull-enriched pasta's cooking quality and nutritional, antioxidant, mineral, and microstructural characteristics.

The value addition of underutilized legume hulls from moong bean, black gram, and chickpea as useful pasta ingredients makes this work novel. It addresses sustainable waste management as well as nutritional improvement. This study offers a thorough evaluation of the effects of hull substitution on the sensory attributes, cooking quality, nutritional composition, antioxidative potential and microstructural properties of pasta, in contrast to previous research studies, which have concentrated on single hull types or restricted quality parameters. This research promotes the creation of functional, nutrient-dense staple foods and advances sustainable food innovation by fusing food waste valorisation with product development. The present study was performed with the aims of evaluating the feasibility of incorporating selected legume hulls into pasta formulations and investigating their impact on nutritional, antioxidative and functional characteristics for their effective utilisation in sustainable food systems.

2 Materials and methods

2.1 Raw materials

The legume hulls of chickpea, black gram and moong bean were obtained from the local market of Bathinda, Punjab, India. The hulls were thoroughly dried (45 °C ± 2 °C, 12 h) and ground into a fine powder. The resulting powders were passed through a 100 μm sieve to ensure a uniform particle size.

2.2 Pasta preparation

The method given by Raina *et al.*[16] was utilized for the preparation of legume hull-enriched pasta samples. For pasta preparation, legume hull flours were mixed with semolina and an optimal amount of water (Table 1) in the extruder's (model: 16 009, Kent, India) mixing chamber for 10 min to create a uniformly mixed dough, which was cold-extruded. The resultant pasta was dried at 45 °C ± 2 °C in a tray dryer (model: Td-12, Narang Scientific Works, India) for 5 h.

Table 1 Formulations of pasta[a]

Sample	Chickpea hull flour (g)	Black gram hull flour (g)	Moong bean hull flour (g)	Semolina (g)	Water (mL)
C	—	—	—	300	100
CP10	30	—	—	270	105
CP20	60	—	—	240	120
CP30	90	—	—	210	150
BP10	—	30	—	270	115
BP20	—	60	—	240	125
BP30	—	90	—	210	160
MP10	—	—	30	270	120
MP20	—	—	60	240	130
MP30	—	—	90	210	170

[a] C-control, CP-chickpea hull pasta, BP-black gram hull pasta, and MP-moong bean hull pasta. The suffixes 10, 20 and 30 represent the level of incorporation (%) of the respective legume hulls.

2.3 Cooking quality

The cooking properties of the pasta were measured using the methods outlined by Demir and Bilgicli[17] for the minimum cooking time (min), water absorption capacity (%), volume expansion (%) and gruel solid loss (%).

2.4 Sensory evaluation

Twenty-five semi-trained panellists from the Department of Food Science and Technology, Maharaja Ranjit Singh Punjab Technical University, Bathinda, Punjab, conducted sensory evaluation of cooked pasta samples. The prepared samples were analysed using a 9-point hedonic scale. Sensory evaluation was conducted in terms of the colour, flavour, aroma, texture and overall acceptability.[18]

2.5 Proximate composition

Standard methods were utilized for the estimation of the proximate composition.[19] The hot-air oven method was used for the determination of the moisture content. The protein content was analysed using the Kjeldahl method, and a conversion factor of 6.25 was used. The Soxhlet method was utilized for the estimation of the fat content using petroleum ether (40–60 °C) (product code: 65 643, Sisco Research Laboratories (SRL) Pvt. Ltd, Mumbai, India) as an extractant. The samples were incinerated at 550 °C for 5 h in a muffle furnace for gravimetric determination of the ash content. Crude fibre was analysed by digesting the samples with H_2SO_4 (1.25%; product code: 26 400, Molychem India LLP., Mumbai, India) and NaOH (1.25%; product code: 96 311, SRL Pvt. Ltd), followed by incineration of the residues in a muffle furnace at 550 °C for 5 h. The difference method was used to calculate the carbohydrate content by subtracting the protein, fat, ash and fibre contents from 100. The final values were expressed in terms of g/100 g of the dry sample.

2.6 Amino acid composition

Amino acids (lysine, tyrosine, tryptophan, valine, leucine and threonine) were determined using the method described by Toor *et al.*[20] The samples were hydrolyzed with 6 M HCl (product code: 320 331, Sigma-Aldrich Chemicals Pvt. Ltd, USA) for 24 h at 110 °C, followed by analysis using a high-performance liquid chromatography (HPLC) system (Agilent Technologies, USA) equipped with a ZORBAX Eclipse plus-C18 column (4.6 × 150 mm, 3.5 μm).

2.7 *In vitro* protein digestibility (IVPD)

The determination of protein digestibility of the legume hull-enriched pasta samples was done by utilizing a method reported by Setia *et al.*[21] Protease (1.3 mg mL^{-1}, *Streptomyces griseus*, ≥15 units mg^{-1} solid) (product code: P5147, Sigma-Aldrich Chemicals Pvt. Ltd), chymotrypsin (3.1 mg mL^{-1}, bovine pancreas, ≥40 units mg^{-1} protein) (product code: 35 085, SRL Pvt. Ltd) and trypsin (1.6 mg mL^{-1}, porcine pancreas, 13 000–20 000 BAEE units mg^{-1} protein) (product code: T0303, Sigma-Aldrich Chemicals Pvt. Ltd) were mixed in distilled water for the preparation of the multi-enzyme solution, which was stored at 37 °C for further analysis. The quantity of the sample equivalent to 62.5 mg of protein was weighed and mixed with 10 mL of distilled water. The prepared contents were incubated at 37 °C for 1 h in a water bath, followed by pH adjustment to 8.0 ± 0.05 utilizing 0.1 M NaOH (product code: 96 311, SRL Pvt. Ltd) or HCl (product code: 320 331, Sigma-Aldrich Chemicals Pvt. Ltd). After that, 1 mL of the multi-enzyme solution was added, followed by incubation at 37 °C for 10 min. Subsequently, the pH of the mixture was noted down and used for calculations as follows:

$$\text{IVPD (\%)} = 65.55 + 18.10 \times \Delta \text{pH}_{10\text{min}}.$$

2.8 Mineral profile

A solution of distilled nitric acid (product code: 438 073, Sigma-Aldrich Chemicals Pvt. Ltd) (3 parts) and perchloric acid (product code: 244 252, Sigma-Aldrich Chemicals Pvt. Ltd) (1 part) was used to digest each sample for 45 min at 90 °C to 95 °C. After dilution with distilled water, the digested solution was filtered and analysed by inductively coupled plasma optical emission spectrometry (ICP-OES; model: iCAP 6300; Thermo Fisher Scientific, USA).[22]

2.9 Phenolic acid composition

According to the procedure outlined by Xiao *et al.*,[23] the samples were extracted using 80% methanol (product code: 79 345, SRL Pvt. Ltd) at a ratio of 1 : 40 w/v at 50 °C for 4 h, after which they were cooled to room temperature. The extracts were centrifuged (model: BS-SP-70BL, Biogenix System, India) for 15 min at 10 000 rpm; the solvent was then evaporated under low pressure, and the residue was dissolved in 80% methanol. An HPLC system (Agilent Technologies, USA) equipped with a reverse-phase ZORBAX Eclipse XRD-phenyl column (4.6 × 250 mm, 5 μm particle size) and a gradient elution solution was used to filter the final solution after passing it through a syringe filter (0.45 μm PVDF membrane). The results were reported as $\mu g\ g^{-1}$ of the sample.

2.10 Pasting properties

The pasting properties of the pasta samples were measured using a rapid visco analyzer (model: RVA Starch Master 2, Perten, Australia). The aluminium RVA canister was filled with 3 g of the powdered sample, followed by the addition of 24.5 mL of distilled water. Parameters such as peak time (min), peak temperature (°C), pasting temperature (°C), peak viscosity (cP), breakdown viscosity (cP) and final viscosity (cP) were recorded.[24]

2.11 Fourier transform infrared (FTIR) spectroscopy

The dried samples were ground into a fine powder, combined with potassium bromide (product code: 451 010, Sigma-Aldrich Chemicals Pvt. Ltd) at a weight ratio of 1 : 100, and compressed at 10 000 psi. Following the method outlined by Wang *et al.*,[25] FTIR spectra in the wavenumber range from 400 to 4000 cm^{-1} were analysed using an FTIR spectrophotometer (model: Tensor 27, Bruker, Germany) in the transmission mode.

2.12 Scanning electron microscopy (SEM)

The microstructure of the pasta samples was examined using a scanning electron microscope (model: Merlin Compact, Carl Zeiss, Germany). The samples were placed on a black carbon tape, and gold was sputter-coated using vacuum evaporation. The photographs were taken at 1200× magnification.[26]

2.13 Statistical analysis

Data are presented as mean ± standard deviation and analysed using one-way analysis of variance (ANOVA) at the $p < 0.05$ significance level with SPSS 19.0 software.[27] Principal component analysis (PCA) was carried out using GraphPad Prism 9.0.0 to understand the influence of hull incorporation on the cooking quality and organoleptic properties of the pasta.

3 Results and discussion

3.1 Cooking quality of legume hull-incorporated pasta

Legume hull incorporation at 10%, 20% and 30% levels significantly ($p < 0.05$) influenced the cooking quality of pasta, as reported in Table 2. The control pasta showed the lowest minimum cooking time of 11.30 min. Adding chickpea hulls at 10%, 20%, and 30% increased the minimum cooking time to 12.53, 12.13 and 14.23 min, respectively; black gram hull incorporation at 10%, 20% and 30% increased the cooking time to 12.25, 12.77 and 14.33 min, respectively; and moong bean hull incorporation at 10%, 20%, and 30% resulted in cooking times of 12.23, 13.13, and 13.23 min, respectively. Kaya *et al.*[14] found that the optimum cooking time of noodles that were substituted with 2.5%, 5% and 10% of different pulse hulls increased to 10, 11 and 12 min, respectively. The study by Foschia *et al.*[28] also reported that the increase in the cooking time was considerable for all fibre-fortified pasta blends of oat bran, psyllium, glucomannan, and inulin. Espinosa-Solis *et al.*[29] identified that the lowest cooking time was for pasta prepared using 100% durum semolina (7.1 min), and pasta fortified with oat bran and apple flour took 8.1 and 8.5 min to cook, respectively. The extended cooking time associated with the addition of hulls could be explained by the fact that dietary fibre is more abundant, which leads to a change in the pasta's microstructure. The addition of fibre causes gluten-starch matrix dilution, decreasing the permeability of the matrix and delaying the rate at which water enters the pasta core. Further, fibre and starch may compete for water, thus slowing down starch gelatinization, which increases the minimum cooking time.[30]

The control sample had the lowest water absorption of 115.5%. In hull-incorporated pasta, the water absorption significantly ($p < 0.05$) increased with the level of substitution of chickpea hull, black gram hull and moong bean hull, with values in the range of 124.72–156.83%, 101.90–144.56% and 121.42–153.77%, respectively. Costantini *et al.*[15] reported that incorporating 8% chickpea hull into gluten-free pasta significantly increased water absorption, indicating that the hull promotes greater water uptake during cooking. Similarly, Kaur *et al.*[30] reported that pasta prepared from semolina absorbed about 117.7% water during cooking, with cereal brans significantly increasing water absorption beyond the 5% level, with the highest increase observed in 25% rice bran-enriched pasta. The increase in water absorption is attributed to the strong water-binding ability of fibre. A higher fibre content leads to an increase in water absorption by increasing the hull or bran content in the resultant pasta. The high water-absorption capacity of fibre may be the cause of increased water absorption. Bran or hull particles encourage water absorption and make it easier for starch granules to inflate and rupture by disrupting the protein matrix.[31]

A similar trend was observed for volume expansion values, wherein the control pasta had the lowest volume expansion of 125.25%. The samples containing chickpea hull (178.79–226.69%), black gram hull (138.45–199.23%) and moong bean hull (178.28–233.28%) exhibited significantly ($p < 0.05$) higher values. The increase for hull-incorporated pasta samples is explained by the fact that they contain more dietary fibre, which helps in the absorption of water during cooking. The fibre components have strong water-binding properties and hydrate the matrix, resulting in swelling and expansion. Further, the gluten network disruption, which may be caused partially by hull incorporation, could permit higher water uptake and structural relaxation, thus contributing to further expansion in

Table 2 Cooking quality of legume hull-incorporated pasta[a]

Sample	Minimum cooking time (min)	Water absorption (%)	Volume expansion (%)	Gruel solid loss (%)
C	11.30 ± 0.20^{e}	115.5 ± 0.01^{h}	125.25 ± 0.05^{h}	2.72 ± 0.01^{e}
CP10	12.53 ± 0.08^{d}	130.10 ± 0.03^{e}	179.78 ± 0.11^{e}	3.30 ± 0.01^{d}
CP20	12.13 ± 0.09^{d}	124.72 ± 0.01^{f}	178.79 ± 0.01^{e}	3.62 ± 0.01^{d}
CP30	14.23 ± 0.03^{a}	156.82 ± 0.05^{a}	226.69 ± 0.12^{b}	4.80 ± 0.02^{b}
BP10	12.25 ± 0.21^{d}	101.90 ± 0.01^{i}	138.45 ± 0.13^{g}	2.29 ± 0.01^{g}
BP20	12.77 ± 0.02^{c}	131.45 ± 0.42^{d}	157.59 ± 0.19^{f}	3.57 ± 0.01^{d}
BP30	14.33 ± 0.08^{a}	144.56 ± 0.04^{c}	199.23 ± 0.01^{c}	4.15 ± 0.02^{c}
MP10	12.23 ± 0.07^{d}	121.42 ± 0.01^{g}	178.28 ± 0.50^{e}	2.46 ± 0.01^{f}
MP20	13.13 ± 0.09^{b}	131.94 ± 0.15^{d}	183.54 ± 0.06^{d}	3.42 ± 0.01^{d}
MP30	13.23 ± 0.04^{b}	153.77 ± 0.01^{b}	233.28 ± 0.02^{a}	5.31 ± 0.04^{a}

[a] C-control, CP-chickpea hull pasta, BP-black gram hull pasta, and MP-moong bean hull pasta. The suffixes 10, 20 and 30 represent the level of incorporation (%) of the respective legume hulls. Values are presented as mean ± standard deviation of three replicates. Means with different superscripts (a–i) depict the significant differences ($p < 0.05$).

the volume.[14] Kaur *et al.*[30] reported that the volume expansion of pasta increased with cereal bran addition, rising from 0.94% in semolina pasta to 1.26% in 25% barley bran pasta. A strong positive correlation ($r = 0.79$ to 0.94) was found between water absorption and volume expansion, showing that higher fibre levels promote greater swelling during cooking, which is similar to the above-mentioned results.

The gruel solid loss values for pasta samples with added legume hulls showed an increasing trend as the level of hull incorporation increased across all three legume types. The control pasta had the lowest gruel solid loss of 2.72%. The intact gluten network encapsulates starch granules, reducing the solubilization of amylose and other components during cooking. This increased significantly ($p < 0.05$) for hull-incorporated pasta, with the maximum values being observed at the 30% incorporation level for chickpea hull (4.80%), black gram hull (4.15%) and moong bean hull (5.31%). Kaur *et al.*[30] observed an increase in cooking loss in pasta fortified with bran from different cereals, such as wheat, rice, barley, and oats. Kaya *et al.*[14] reported that adding green lentil, red lentil, faba bean, and pea hulls to noodles at 2.5%, 5%, or 10% generally did not significantly affect cooking loss, except for pasta with faba bean hulls, which showed a notable gruel solid loss compared to the control. Brennan *et al.*[31] also observed that adding dietary fibre to pasta led to higher cooking loss and reduced firmness compared with the control pasta. Sobota *et al.*[32] also reported that the addition of wheat bran (from 20% to 40%) to semolina caused a linear increase in cooking loss. However, the leaching of soluble proteins and starches during cooking is facilitated by a weakened protein matrix and greater structural discontinuities, which result in a higher loss of gruel solids. The incorporation of hulls dilutes the protein matrix and disrupts the continuity of the gluten network, thereby weakening the structural framework responsible for entrapping starch granules during cooking. These effects intensify as the concentration of hull increases, indicating that the main factor influencing the cooking quality of enriched pasta is structural alteration brought on by fibre.

Le *et al.*[33] conducted a study that demonstrated that the use of moong bean by-product flour for pasta preparation had a significant impact on essential cooking parameters such as optimal cooking time, cooking loss, and swelling index. In particular, increasing the percentage of moong bean by-product flour from 0% to 25% decreased the optimum cooking time from 13.5 to 11.0 min, and this was attributed to the lower starch content and partial disruption of the gluten network, which enabled faster water absorption and starch gelatinization. At the same time, the cooking loss became increasingly extensive (4.0% to 6.9%), which indicated a decrease in the strength of protein-starch interactions and the leaching of soluble substances into the cooking water. The swelling index changed slightly but significantly at the maximum substitution level (25% moong bean by-product flour), indicating that lower starch concentrations and the altered network structure inhibit the system's water absorption and granule swelling during cooking. These observations demonstrate that while dietary fibre enrichment may slightly compromise structural stability, formulations containing up to 20% moong bean by-product flour maintain acceptable cooking quality parameters for pasta development.

3.2 Sensory evaluation of pasta

The sensory evaluation results (Fig. 1) showed noticeable differences in the colour, flavour, aroma, texture, and overall acceptability among the formulations (10% to 30%). The control pasta was found to score high across the categories. Incorporation of legume hulls at 20% tended to maintain or slightly improve the sensory quality, whereas substitution at a higher level (30%) decreased the panel scores progressively. There was a slight variation in colour scores with an increase in the hull content because hulls have darker pigments and natural seed-coat compounds. Fibre-rich fractions of the bran or hull normally darken pasta because of phenolic compounds and colour in the outer seed cover. Despite this effect, moderate substitution levels (20%) maintained acceptable colour perception among panellists. At the lowest and intermediate levels of hull incorporation, flavour and aroma scored well, with

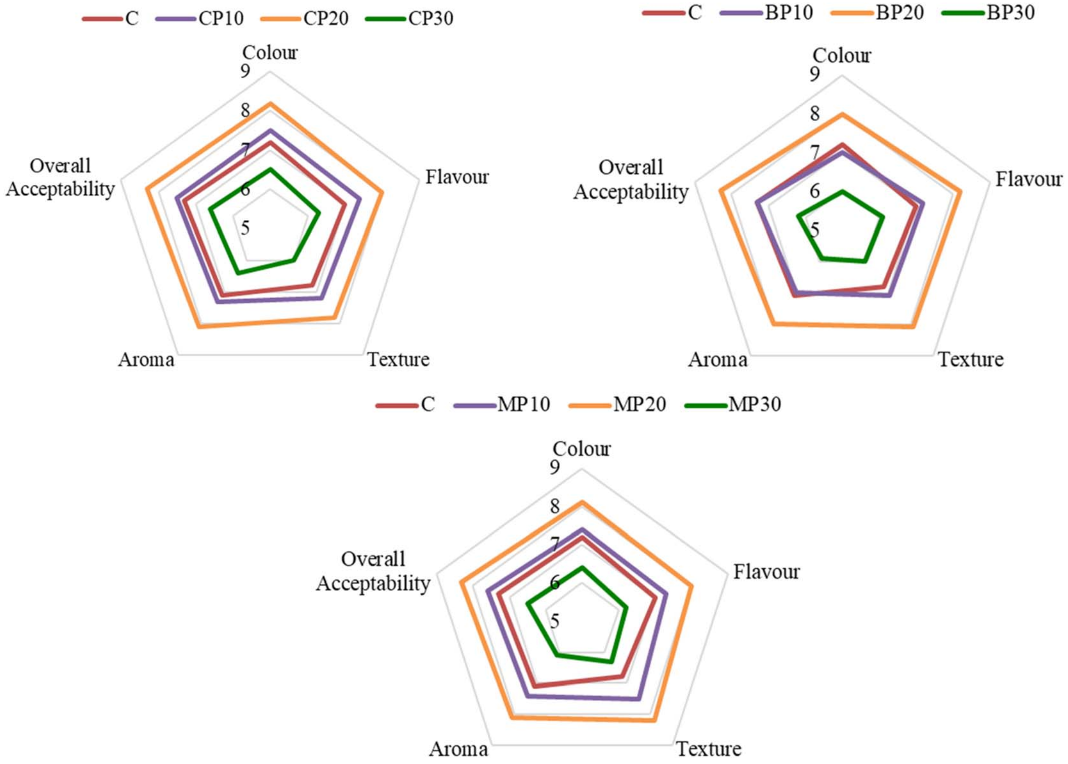


Fig. 1 Sensory evaluation of legume hull-incorporated pasta. C-control, CP-chickpea hull pasta, BP-black gram hull pasta, and MP-moong bean hull pasta. The suffixes 10, 20 and 30 represent the level of incorporation (%) of the respective legume hulls.

marginally lower scores at the highest incorporation. The marginally reduced value is probably caused by the earthy flavour and volatile compounds in the hull fractions that increase at higher concentrations. Texture showed the most pronounced changes with increasing hull incorporation. Fibre-rich ingredients such as pulse hulls interfere with gluten network formation by diluting gluten proteins and disrupting the continuous starch-protein matrix in the control pasta. As a result, the structural firmness and hardness of pasta can increase, while cohesiveness may decrease. Studies on fibre-enriched pasta have reported that the incorporation of bran or legume flour leads to increased hardness and reduced elasticity due to the presence of insoluble dietary fibre particles within the dough matrix.[34]

According to Kaur *et al.*,[30] increasing the level of cereal bran incorporation in pasta formulations significantly decreased sensory scores, including colour, flavour, texture, and overall acceptability, mainly due to the high fibre content and its interference with the gluten–starch matrix. Similarly, Gajula *et al.*[35] found that increasing the amount of bran in raw flour from 0% to 25% considerably decreased the tortillas' overall acceptability as well as all other characteristics. A 20% level of millet flour mix integration was determined to be suitable for the creation of noodles, according to Vijayakumar *et al.*[36] This shows that moderate incorporation (20%) of chickpea, black gram, and moong bean hulls results in the highest sensory scores, whereas 30% incorporation leads to a decline in quality attributes. Thus, based on the sensory profile illustrated, 20% hull incorporation appears to provide the most balanced and acceptable pasta among all formulations.

3.3 Principal component analysis (PCA)

Principal component analysis (Fig. 2) showed the contribution of the first (73.35%) and second (20.55%) principal components to the general variability (93.9%) of the plotted data. The positive, negative and no correlations among the properties were exhibited by acute (<90°), obtuse (>90°) or straight (180°), and right (90°) angles between the vectors, respectively. It was observed that a higher minimum cooking time led to increased water absorption, volume expansion and gruel solid loss but also reduced the sensory scores. The distance between the sample coordinates was directly proportional to the similarity degree amongst them. From the biplot, it was clearly observed that an increase in the substitution levels of legume hull proportionately enhanced the minimum cooking time, water absorption, volume expansion and gruel solid loss but reduced the organoleptic scores. However, for all the legume hulls, an optimal balance was observed for the pasta substituted with the 20% level.

Based on this, the pasta samples prepared *via* the incorporation of 20% legume hulls were selected for further analysis.

3.4 Proximate composition of legume hull-incorporated pasta

The proximate composition of pasta samples prepared *via* the incorporation of 20% chickpea hull, black gram hull, and

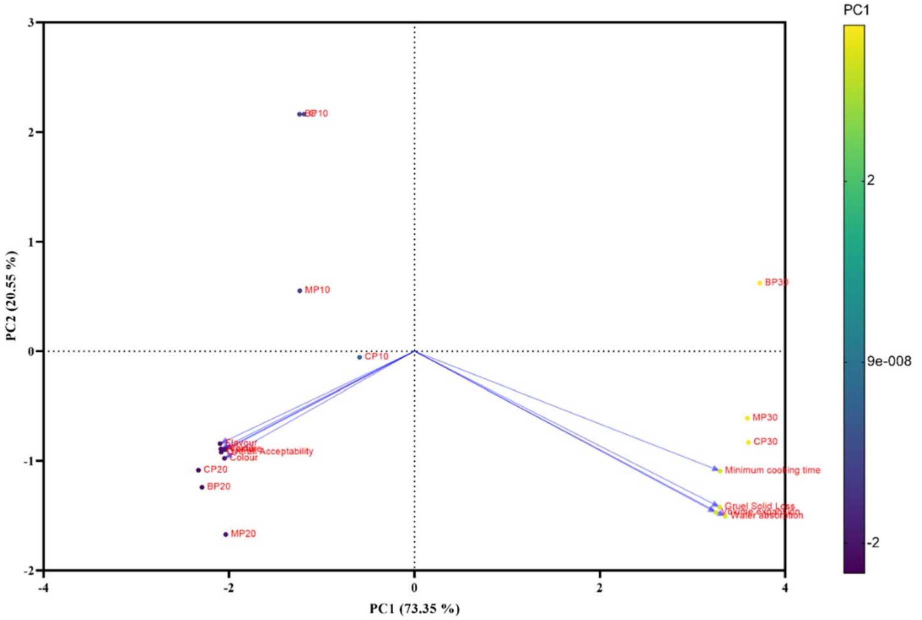


Fig. 2 Principal component analysis (PCA) biplot showing the relationships between the pasta samples and the cooking and organoleptic qualities. CP-chickpea hull pasta, BP-black gram hull pasta, and MP-moong bean hull pasta. The suffixes 10, 20 and 30 represent the level of incorporation (%) of the respective legume hulls.

moong bean hull was analysed and is tabulated in Table 3. The results revealed a significant ($p < 0.05$) increase in the ash, fat, and fibre contents across all hull-incorporated pasta samples, whereas moisture and protein values showed no significant variation. However, incorporating legume hulls into pasta reduced the carbohydrate content from 75.83 to 64.60 g/100 g. The findings are also supported by the study of Gunarathne *et al.*,[37] in which the authors showed a higher carbohydrate content in wheat flour (76.40%) than in a coconut testa flour admixture containing 25% coconut testa flour (65.12%). The consistent moisture content across samples indicated the storage stability of hull-incorporated pasta.[37] The ash content increased by 159%, 22%, and 158% for CP20, BP20, and MP20 samples, respectively, which is in agreement with the findings of Le *et al.*,[33] who stated that moong bean by-product flour-enriched pasta exhibited a 6 times higher ash content than durum pasta. In the present study, the fat content of chickpea hull-, black gram hull-, and moong bean hull-incorporated pasta increased by 1.94, 3.26, and 2.96 times, respectively. In this context, Sabouni *et al.*[38] reported that the fat content of legume hulls ranges from 0.15% to 0.91%, adding to the fat content of legume hull-enriched pasta. The fibre content of hull-incorporated pasta also increased with 20% substitution, from 2.10 g/100 g in the control to 4.26, 7.07, and 8.15 g/100 g in CP20, BP20, and MP20 samples, respectively. Costantini *et al.*[15] confirmed that legume hull incorporation significantly enhances the total fibre content. The increase in fibre is attributed to the high level of fibre in the legume hulls, especially due to the insoluble fibre in the seed coat.[12] Furthermore, the carbohydrate content was higher in the control pasta but reduced by 7.97%, 13.41%, and 14.81% in CP20, BP20, and MP20, respectively.

3.5 Amino acid composition of legume hull-incorporated pasta

The amino acid composition plays an important role in determining the protein quality of a plant protein source. Legume hull incorporation enhanced the contents of lysine, tyrosine,

Table 3 Proximate composition (g/100 g) of legume hull-incorporated pasta[a]

Parameter	C	CP20	BP20	MP20
Moisture	8.82 ± 0.16^a	8.83 ± 0.17^a	8.81 ± 0.15^a	8.31 ± 0.33^a
Ash	0.99 ± 0.06^c	2.56 ± 0.36^a	1.21 ± 0.06^b	2.55 ± 0.16^a
Fat	2.22 ± 0.04^d	4.31 ± 0.08^c	7.24 ± 0.08^a	6.58 ± 0.02^b
Protein	10.04 ± 0.09^a	10.25 ± 0.15^a	10.01 ± 0.11^a	9.81 ± 0.17^a
Fibre	2.10 ± 0.03^d	4.26 ± 0.05^c	7.07 ± 0.07^b	8.15 ± 0.09^a
Carbohydrates	75.83 ± 0.28^a	69.79 ± 0.22^b	65.66 ± 0.24^c	64.60 ± 0.30^d

[a] C-control, CP-chickpea hull pasta, BP-black gram hull pasta, and MP-moong bean hull pasta. The suffix 20 represents the level of incorporation (%) of the respective legume hulls. Values are presented as mean ± standard deviation of three replicates. Means with different superscripts (a–d) depict the significant differences ($p < 0.05$).

Table 4 Amino acid composition (% of protein) of legume hull-incorporated pasta[a]

Amino acid	C	CP20	BP20	MP20
Lysine	2.85	3.09	3.19	3.22
Tyrosine	1.30	1.52	1.52	1.58
Tryptophan	1.83	2.03	2.04	2.16
Valine	2.47	2.71	2.80	2.90
Leucine	1.50	1.66	1.76	1.84
Threonine	1.51	2.99	2.87	3.50

[a] C-control, CP-chickpea hull pasta, BP-black gram hull pasta, and MP-moong bean hull pasta. The suffix 20 represents the level of incorporation (%) of the respective legume hulls.

tryptophan, valine, leucine and threonine in pasta (Table 4). MP20 showed the highest increase for all the amino acids, wherein the highest elevation of 131.79% was observed in the values of threonine compared to the control pasta. Simultaneously, CP20 and BP20 showed a moderate increase in all the amino acids, with the maximum elevation of 98.01% and 90.07%, respectively, observed in threonine. Lysine, tyrosine, tryptophan, valine and leucine contents increased in the ranges of 8.42–12.98%, 16.92–21.54%, 10.92–18.03%, 9.72–17.41% and 10.67–22.67% of protein, respectively. Alzuwaid *et al.*[39] also observed an increase of 7.59% in the total essential amino acids in spaghetti enriched with 20% wheat bran protein concentrate compared with 3.76% in the control. Similarly, Manthey and Hall III[40] also reported that the lysine content in uncooked and cooked spaghetti containing buckwheat bran flour increased by 147.71–168.53% and 79.71–100.25%, respectively. Conclusively, the incorporation of chickpea, moong bean and black gram hulls increased the concentration of all the analysed amino acids, even though the protein concentration (Table 3) remained stable.

3.6 *In vitro* protein digestibility of legume hull-incorporated pasta

In vitro protein digestibility provides critical information on the protein quality and amino acid bioavailability by simulating the human digestive system in a laboratory.[41] All samples exhibited high *in vitro* protein digestibility, ranging from 77.51% to 80.05% (Fig. 3). While the control pasta showed a protein digestibility value of 80.05%, the incorporation of 20% moong bean and black gram hulls resulted in significant ($p < 0.05$) but minor reductions of 2.5% and 3.17%, respectively. In contrast, CP20 showed no significant variation compared to the control sample. These results depicted that incorporating legume hulls did not adversely affect the protein quality in pasta. The slight reduction observed in the digestibility of certain samples could be attributed to the higher fibre content of hulls, which created a physical barrier around protein matrices, thereby limiting enzyme accessibility during *in vitro* digestion. A recent study by Rodriguez-Huezo *et al.*[42] reported a decrease in the *in vitro* protein digestibility of semolina pasta upon the incorporation of soluble dietary fibre. The control pasta exhibited a high *in vitro* protein digestibility of 91.87%, whereas the addition of green pea fibre, corn fibre, and polydextrose at 18 g/100 g reduced digestibility to 32.40%, 54.05%, and 25.98%, respectively ($p < 0.05$). Similar findings were reported by Segura-Campos *et al.*,[43] who observed a decrease in protein digestibility from 86.5% in the control pasta to 75.2% in pasta containing 10% *Phaseolus vulgaris* L. flour, and they stated that the high digestibility values observed in both pastas were probably the result of protein denaturation by extrusion, which may increase the exposure of sites susceptible to enzymatic activity.

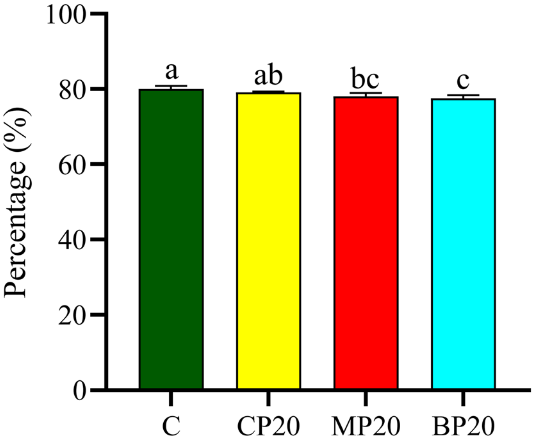


Fig. 3 *In vitro* protein digestibility of legume hull-incorporated pasta. C-control, CP-chickpea hull pasta, BP-black gram hull pasta, and MP-moong bean hull pasta. The suffix 20 represents the level of incorporation (%) of the respective legume hulls. Error bars represent the standard deviation of the mean values of three replicates. Different letters on bars depict the significant differences ($p < 0.05$).

3.7 Mineral profile of legume hull-incorporated pasta

Table 5 displays the mineral contents in hull-incorporated pasta formulations. The control pasta exhibited the highest levels of potassium (303.71 mg/100 g) and selenium (0.59 µg/100 g). The potassium dominance is likely due to the inherent mineral composition of semolina. The selenium content showed minimal variation among all samples, ranging narrowly between 0.51 and 0.59 µg/100 g. This variability may be attributed to various environmental factors such as soil conditions, fertilizer application levels and type of processing at the post-harvest stage.[44] MP20 demonstrated the highest concentrations of magnesium (150.27 mg/100 g), zinc (4.33 mg/100 g), and manganese (4.30 mg/100 g). BP20 outperformed other variants in calcium (29.77 mg/100 g), while the control pasta showed the highest phosphorus content (385.37 mg/100 g). These values align with the study by Kamani and Meera,[4] who reported that black gram milling by-products are rich in macrominerals, particularly calcium, due to their concentration in seed coats. CP20 exhibited the highest iron concentration (4.15 mg/100 g), signifying a key role in haemoglobin synthesis and oxygen transport. CP20 also retained considerable levels of zinc (4.02 mg/100 g) and magnesium (124.19 mg/100 g), indicating that chickpea hulls can provide a well-rounded mineral contribution to functional food development. As a good source of zinc and iron, chickpea hulls can play a vital role in

Table 5 Mineral profile of legume hull-incorporated pasta[a]

Element	C	CP20	BP20	MP20
Calcium (mg/100 g)	28.17	23.74	29.77	26.76
Magnesium (mg/100 g)	136.18	124.19	110.96	150.27
Zinc (mg/100 g)	3.15	4.02	3.54	4.33
Manganese (mg/100 g)	4.18	3.34	3.92	4.30
Iron (mg/100 g)	3.26	4.15	3.49	3.81
Copper (mg/100 g)	0.33	0.30	0.33	0.36
Selenium (μg/100 g)	0.59	0.57	0.51	0.53
Phosphorus (mg/100 g)	385.37	334.02	321.52	350.80
Potassium (mg/100 g)	303.71	257.75	249.76	298.67
Sodium (mg/100 g)	9.75	10.37	12.04	9.13

[a] C-control, CP-chickpea hull pasta, BP-black gram hull pasta, and MP-moong bean hull pasta. The suffix 20 represents the level of incorporation (%) of the respective legume hulls.

overcoming hidden hunger. The contents of iron and zinc in chickpeas range from 4.56 mg/100 g to 9.87 mg/100 g and 0.96 mg/100 g to 4.05 mg/100 g, respectively.[45] The copper content remained relatively uniform across all samples, ranging narrowly between 0.30 and 0.36 mg/100 g, with the highest value being recorded in MP20. Copper is a trace element that plays a critical role in enzymatic redox reactions and connective tissue synthesis. Regarding sodium, a modest variation was observed, with BP20 registering the highest content (12.04 mg/100 g), possibly due to salt residues from processing or the intrinsic sodium content in the hull material. BP20 (9.13 mg/100 g), CP20 (10.37 mg/100 g), and the control sample (9.75 mg/100 g) followed closely, indicating the minimal influence of hull addition on the overall sodium content.

Kaya *et al.*,[14] in their work on Turkish noodles fortified with lentil, pea, and faba bean hulls (2.5–10%), observed a general increasing trend in calcium and magnesium contents across all hull types, with red lentil hull substitution at 10% producing nearly a 5× increase in the mineral content compared to the control. Similarly, magnesium contents rose by 36–70% depending on the hull type, with pea hull substitution showing the highest increase. Such findings reinforce the role of hull incorporation as a sustainable food approach, valorizing legume processing by-products for nutritional enrichment.[46] However, differences in soil type and fertilizer applications influence the mineral composition of the legumes and their hulls; therefore, the mineral results cannot be generalized.[47]

3.8 Phenolic acid composition of legume hull-incorporated pasta

The primary source of dietary antioxidants is thought to be phenolic acids, and it has been proposed that the antioxidant activity of these molecules is caused by the phenolic hydroxyl groups that are connected to their ring structures.[48] The phenolic composition of the pasta samples showed clear differences based on the type of legume hull used, as shown in Table 6. Among all the samples, BP20 exhibited the highest concentration of most compounds, suggesting its superior potential for polyphenolic enrichment. The catechin content was highest in BP20 (15.57 μg g^{-1}), exceeding the control (14.95 μg g^{-1}). Gallic acid was the most abundant in the control (3.78 μg g^{-1}), with BP20 (3.49 μg g^{-1}) showing a similar profile, while MP20 had the lowest (3.31 μg g^{-1}) value. These findings are consistent with the results reported by Rani *et al.*,[49] who extensively characterized the polyphenolic profile of black gram and identified high concentrations of catechin (34.12 μg g^{-1}), syringic acid (28.34 μg g^{-1}), ferulic acid (23.87 μg g^{-1}), and coumaric acid (22.56 μg g^{-1}) in its seed hull extracts. Hydroxybenzoic acid followed a similar pattern, with the highest value in the control (3.57 μg g^{-1}) and the lowest value in MP20 (3.10 μg g^{-1}). Notably, the coumaric acid content was higher in BP20 (29.63 μg g^{-1}) while MP20 recorded the lowest value (26.48 μg g^{-1}). The content of chlorogenic acid, another significant phenolic compound, was slightly higher in BP20 (2.72 μg g^{-1}), with MP20 again showing the lowest level (2.43 μg g^{-1}), and the levels were similar in the control and CP20. The caffeic acid content followed a similar trend, with the highest content in BP20 (7.24 μg g^{-1}) and the lowest content in MP20 (6.47 μg g^{-1}). Luo *et al.*[50] reported that legume hulls exhibited a high total phenolic content, reaching up to 29.2 mg GAE per g. Their study also highlighted that phenolic acids such as ferulic, *p*-coumaric, and syringic acids are predominantly present in the hulls, confirming the phenolic enrichment observed in hull-fortified pasta formulations. Syringic acid, known for its antioxidant and anti-inflammatory properties, was the most prevalent in BP20 (14.94 μg g^{-1}) and the least prevalent in MP20 (13.36 μg g^{-1}), with CP20 and the control showing similar contents. Finally, the content of ferulic acid, which helps maintain the plant cell wall structure and offers notable nutraceutical benefits, was the highest in BP20 (7.13 μg g^{-1}) and the lowest in MP20 (6.37 μg g^{-1}). Duenas *et al.*[51] reported that the seed coat of lentils contains 51.7 μg g^{-1} of syringic acid and 35.2 μg g^{-1} of *p*-coumaric acid, markedly higher than in the cotyledon. This highlights the potential of hulls as a sustainable source of phenolic acids, supporting the development of functional foods.

Table 6 Phenolic acid (μg g^{-1}) composition of legume hull-incorporated pasta[a]

Compound	C	CP20	BP20	MP20
Catechin	14.95	14.78	15.57	13.99
Gallic acid	3.78	3.68	3.49	3.31
Hydroxybenzoic acid	3.57	3.47	3.29	3.10
Coumaric acid	28.27	28.12	29.63	26.48
Chlorogenic acid	2.59	2.58	2.72	2.43
Caffeic acid	6.90	6.86	7.24	6.47
Syringic acid	14.26	14.18	14.94	13.36
Ferulic acid	6.80	6.76	7.13	6.37

[a] C-control, CP-chickpea hull pasta, BP-black gram hull pasta, and MP-moong bean hull pasta. The suffix 20 represents the level of incorporation (%) of the respective legume hulls.

Table 7 Pasting properties of legume hull-incorporated pasta[a]

Characteristic	C	CP20	BP20	MP20
Peak time (min)	8.37 ± 0.00^{b}	8.43 ± 0.00^{ab}	8.48 ± 0.02^{a}	8.38 ± 0.02^{b}
Pasting temperature (°C)	63.75 ± 0.75^{a}	63.50 ± 0.10^{a}	59.90 ± 0.40^{b}	59.90 ± 0.30^{b}
Peak temperature (°C)	95.05 ± 0.05^{a}	95.30 ± 0.00^{a}	95.30 ± 0.00^{a}	95.10 ± 0.1^{a}
Peak viscosity (cP)	2985 ± 43^{a}	1614 ± 8.5^{b}	1745 ± 15^{b}	1402 ± 39^{c}
Breakdown (cP)	1696 ± 67^{a}	713.55 ± 3.95^{b}	772.55 ± 14.75^{b}	686.30 ± 26.8^{b}
Final viscosity (cP)	2990 ± 12^{a}	1895 ± 11^{c}	2173 ± 2.5^{b}	1615 ± 34.5^{d}

[a] C-control, CP-chickpea hull pasta, BP-black gram hull pasta, and MP-moong bean hull pasta. The suffix 20 represents the level of incorporation (%) of the respective legume hulls. Values are presented as mean ± standard deviation of two replicates. Means with different superscripts (a–d) depict the significant differences ($p < 0.05$).

3.9 Pasting properties of legume hull-incorporated pasta

Results of the pasting properties of legume hull-incorporated pasta are presented in Table 7. Peak time is the time starch takes to attain its peak viscosity during the heating–cooling cycle, which indicates the ease of cooking. The peak time varied in the following order: BP20 (8.48 min) > CP20 (8.43 min) > MP20 (8.38 min) > control (8.37 min). Studies have reported that the incorporation of hull results in an increased peak time due to less swelling and slow starch gelatinization.[52,53] Pasting temperature is the lowest temperature required for the gelatinization or cooking of pasta. At this temperature, starch granules absorb water and begin to swell, which further results in an increase in viscosity.[54] The control and CP20 exhibited similar pasting temperatures of 63.75 °C and 63.50 °C, respectively, whereas BP20 and MP20 exhibited the same value of 59.9 °C. Singh *et al.*[54] also reported a decrease in the pasting temperature from 87.45 °C to 80.85 °C with the addition of moong bean flour. The pasting temperature varies with the starch type, particle size and processing conditions. The authors also demonstrated that the incorporation of hull results in increased non-starch polysaccharides such as cellulose and hemicellulose, which interact with starch molecules, reducing their thermal stability. This further results in reduced pasting temperatures with the incorporation of hull.[55] The pasting viscosity decreased after the incorporation of hull, with values of 2985, 1614, 1745 and 1402 cP for the control, CP20, BP20 and MP20, respectively. Studies have demonstrated that fibres compete against starch granules due to their greater affinity towards water molecules. This further results in the decreased ability of starch to absorb water, ultimately resulting in decreased pasting viscosities. It can also be inferred from reduced pasting viscosities that the incorporation of hull results in less susceptibility of starch granules to gelatinisation.[52] Breakdown viscosity refers to the difference between the peak viscosity and the trough viscosity. It is an indicator of starch stability and represents how easily starch can collapse after gelatinisation.[54] The breakdown viscosity showed a decreasing trend as follows: control (1696 cP) > BP20 (772 cP) > CP20 (713 cP) > MP20 (686 cP). The decrease in the breakdown viscosity with hull incorporation in pasta has the same reason as the decrease in the pasting viscosity. Jhans *et al.*[52] claimed in their studies that breakdown and peak viscosities represent a number of quality parameters of pasta, such as its stickiness and smoothness. Final viscosity is defined as the ability of a sample to form a viscous paste upon cooling and indicates the retrogradation ability of amylose upon cooling after gelatinization.[56] The final viscosity values also decreased with the incorporation of legume hull, depicting the highest value in the control pasta (2990 cP), followed by BP20 (2173 cP), CP20 (1895 cP) and MP20 (1615 cP). Reduced final viscosity indicates a decreased retrogradation tendency due to the dilution of starch and interference from dietary fibre. The decrement in the final viscosity after the incorporation of legume hull is due to increased non-starch polysaccharides, resulting in less starch availability for water absorption and viscosity development.[57]

3.10 FTIR analysis of legume hull-incorporated pasta

The infrared spectra of pasta samples are presented in Fig. 4. They determine the presence or absence of particular functional groups. The FTIR spectra of the control pasta, chickpea hull pasta, black gram hull pasta, and moong bean hull pasta were compared to determine structural differences utilizing the vibrational patterns of the various functional groups present.[54] The FTIR patterns of all samples were analysed in the

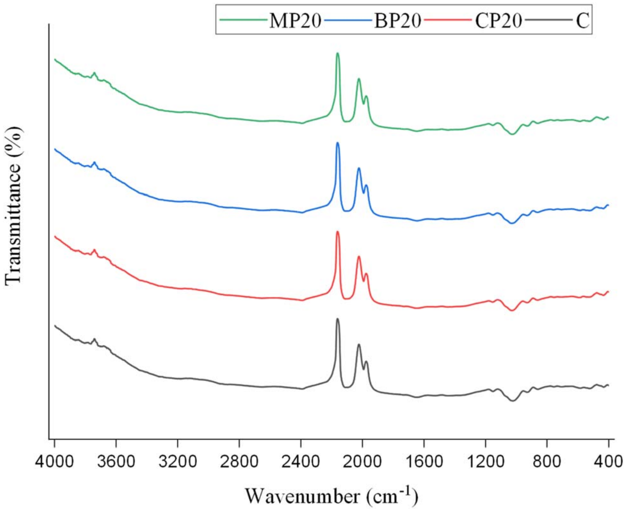
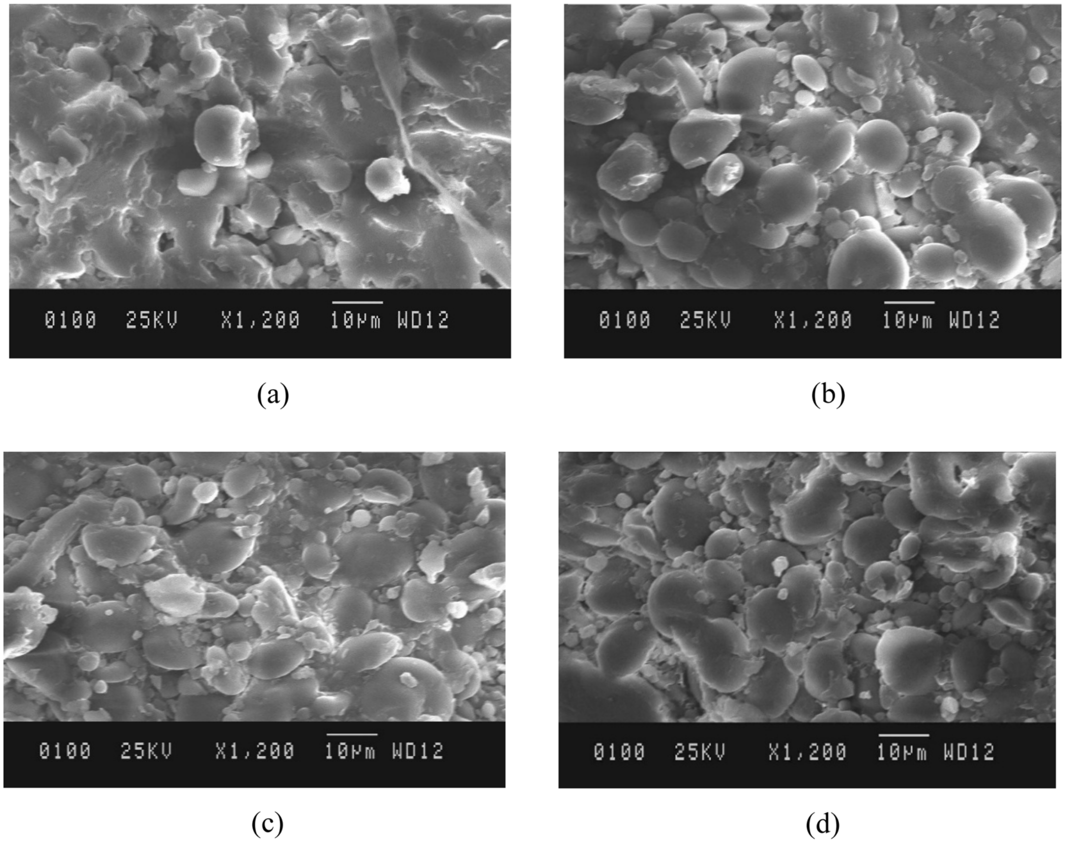


Fig. 4 FTIR spectra of legume hull-incorporated pasta. C-control, CP-chickpea hull pasta, BP-black gram hull pasta, and MP-moong bean hull pasta. The suffix 20 represents the level of incorporation (%) of the respective legume hulls.



(a) (b)

(c) (d)

Fig. 5 SEM images of the pasta samples at the 20% incorporation level of the legume hulls: (a) control, (b) chickpea hull pasta, (c) black gram hull pasta, and (d) moong bean hull pasta.

wavenumber range between 400 and 4000 cm^{-1}. The FTIR spectra of the optimized pasta samples do not show significant differences compared to those of the control pasta, as these samples exhibit similar characteristic absorption peaks at 3763.41, 2393.23, 2109.74, 1992.11, 1644.98, 1152.26, 1023.15, 929.52, 860.096, 523.58 and 431.98 cm^{-1}. A strong and broad absorption band is observed at 3763.41 cm^{-1}, which is attributed to the stretching vibrations of hydroxyl (O–H) groups. This band may arise from O–H groups present in phenolic compounds, alcoholic groups, and water molecules, indicating hydrogen bonding interactions within the pasta matrix.[58] Studies have revealed that O–H stretching results mainly from the hemicellulose present in the hulls of chickpeas, black grams and moong beans.[59] The decreased absorbance in the range of 3600–3200 cm^{-1} in the hull-incorporated samples compared to the control pasta samples indicates the decreased carbohydrate content in the hull-incorporated pasta samples. In the study of Gunarathne *et al.*,[37] the higher intensity of the peaks in the range of 3600–3200 cm^{-1} in wheat samples compared with coconut testa flour-incorporated samples was correlated with a higher content of total carbohydrates. In a similar study by Yilmaz *et al.*,[60] the control pasta had the highest O–H band intensity compared with the cherry powder-enriched pasta. The existence of very strong peaks at 2393.23 and 2109.74 cm^{-1} for the control pasta, chickpea hull pasta, black gram hull pasta, and moong bean hull pasta indicates the presence of C–H stretching vibrations, indicating the presence of groups mainly associated with alkane structures and *cis*-olefinic groups. The presence of the amide II band, which is caused by N–N bond vibrations with C–N stretching, is shown by the transmittance peak that is observed at 1992.11 cm^{-1}. The sharp peak at 1644.98 cm^{-1} represents the amide I band, including the C–O group of the protein peptides and the N–H bending as well as C–N stretch, which are crucial for revealing and analysing the secondary structure of proteins. These similar peaks indicate that hull incorporation into pasta does not induce any major variation in the *in vitro* protein digestibility of pasta, as protein digestibility and the secondary structure of proteins are inversely correlated.[61] The amorphous state of starch granules is linked to the steep peaks that are almost visible at 1023.15 and 1152.26 cm^{-1}, which is important for the characterization of the structure of various carbohydrates.[54] Additionally, the wide band from 1100 cm^{-1} to 800 cm^{-1} with peaks at 929.52 and 860.10 cm^{-1} depicts the greater absorbance of the control sample, indicating the presence of carbohydrates, which mainly represents the fingerprint of starch and pectin. The greater absorbance in this region for the control sample, compared to the hull-incorporated pasta samples, depicts short-range ordered structures, mainly the C–C and C–O stretching and C–O–H bending of different pasta samples, showing variations in starch and other soluble carbohydrates due to the incorporation of hulls.[33,62] Because similar absorption patterns are observed for all samples with different absorbance intensities, it can be concluded that the incorporation of hulls of various legumes does not majorly affect the functional groups of pasta.

3.11 Scanning electron microscopy (SEM) of legume hull-incorporated pasta

Scanning electron microscopy was used to investigate the microstructure and surface morphology of the control pasta and legume hull-incorporated pasta samples. The control sample exhibited a compact morphology with a relatively smooth matrix, indicating protein-starch interactions. The hull-incorporated pasta samples displayed a more disrupted and heterogeneous surface (Fig. 5). With the exception of the control pasta, which displayed predominantly spherical starch granules, the microstructural analyses of the pasta samples revealed that visible starch granules had pores, cracks and rough textures at the surface and were polygonal in shape with edges. This disruption may be attributed to the insoluble dietary fibre present in the hulls, which interferes with the formation of a uniform gluten network, thereby affecting the structural integrity. This weaker structural matrix results in greater cooking loss and gruel solid loss in hull-incorporated pasta.[34] These results are supported by the study of Singh *et al.*,[54] which demonstrated that the addition of moong bean flour (30%) impacts the structural integrity of the pasta, resulting in increased protein and fibre contents, which contribute to a weaker matrix, accounting for greater cooking losses in moong bean-supplemented pasta. These demonstrations are also supported by the study of Raj and Dash[63] on the formulation and characterization of pasta utilizing pearl millet and a dragon fruit pulp powder. A stronger association between protein and starch was shown by the more agglomerated appearance of the starch granules of the control pasta compared to legume hull-incorporated pasta. The addition of chickpea, black gram and moong bean hulls decreased the gluten content, resulting in exposed starch granules, as exhibited by the morphology of these samples. The higher fibre content of all samples, except the control sample, led to the discontinuity of the starch-gluten network, resulting in the appearance of holes and cracks responsible for the leaching of various solid components such as starch, contributing to higher cooking loss of hull-incorporated pasta.[54,62] These results are also an explanation of greater water absorption capacities during the cooking of legume hull-incorporated pasta samples as a result of exposed starch granules.[38] Similar results were also shown by Singh *et al.*,[54] and the authors reported that the incorporation of moong bean flour in barley pasta leads to greater water absorption because the fibre present in the hull tends to trap a greater amount of water, in contrast to the control pasta.

4 Conclusion

The current study aimed to explore the sustainable utilization of legume hull by investigating the potential of chickpea, black gram and moong bean hulls as functional ingredients in pasta formulations. The incorporation of legume hulls significantly influenced cooking, nutritional and functional attributes. Pasta containing 20% hull showed the optimum balance between the cooking quality and sensory acceptability, as revealed by principal component analysis. Hull incorporation significantly increased the levels of fibre and all the analysed amino acids, including lysine, while reducing the carbohydrate content. The minor reduction in the *in vitro* protein digestibility also indicated a shift toward fibre-rich functional pasta formulations. Moreover, hull incorporation influenced the mineral and phenolic contents to varying degrees, alongside modifications in pasting and microstructural characteristics. Conclusively, the integration of legume hulls into food formulations demonstrates their potential as a functional ingredient in the development of value-added foods while promoting sustainable upcycling in food processing.

Although complete amino acid profiling and antinutritional composition characterization are the limitations of the current study, they provide a clear direction for further investigation. Future research should focus on the processing of legume hulls to analyse the changes in their nutritional, functional, antioxidative and structural characteristics. Both unprocessed and processed hulls should be explored in the development of diverse value-added products. *In vivo* models should be utilized to examine the effects of hull incorporation on the digestibility and glycaemic index. Such investigations will strengthen the utilization of legume hulls as a functional ingredient in the development of nutritionally enriched sustainable food products.

Author contributions

Gautam Kumar: data curation, methodology, formal analysis; Kiranbeer Kaur: data curation, writing – original draft; Amandeep Kaur: data curation, writing – original draft; Barinderjeet Singh Toor: conceptualization, project administration, supervision, writing – review and editing; and Ankita Kataria: resources, validation, writing – review and editing.

Conflicts of interest

The authors declare that they have no conflicts of interest.

Abbreviations

BP10	Pasta incorporated with 10% black gram hull
BP20	Pasta incorporated with 20% black gram hull
BP30	Pasta incorporated with 30% black gram hull
C	Control pasta
CP10	Pasta incorporated with 10% chickpea hull
CP20	Pasta incorporated with 20% chickpea hull
CP30:	Pasta incorporated with 30% chickpea hull
FTIR	Fourier transform infrared spectroscopy
HPLC	High-performance liquid chromatography
ICP-OES:	Inductively coupled plasma-optical emission spectrometry

IVPD:	*In vitro* protein digestibility
MP10	Pasta incorporated with 10% moong bean hull
MP20	Pasta incorporated with 20% moong bean hull
MP30	Pasta incorporated with 30% moong bean hull
PCA	Principal component analysis
RVA	Rapid visco analyzer
SDGs	Sustainable development goals
SEM	Scanning electron microscopy

Data availability

The data used have been included in the manuscript.

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