Legume Science

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COMPREHENSIVE REVIEW OPEN ACCESS

Technological Advances in Mung Bean (*Vigna radiata* (L.) Wilczek) Milling, Processing, and Utilization

Suresh Sakhare[1] | Ashlyn Rairdin[2] | Venkata Naresh Boddepalli[2] | Amrita Ray[3] | Arti Singh[2]

[1]Flour Milling, Baking and Confectionary Technology Department, CSIR-Central Food Technological Research Institute, Mysuru, Karnataka, India | [2]Department of Agronomy, Iowa State University, Ames, Iowa, USA | [3]Northern Crop Institute (NCI), Fargo, North Dakota, USA

Correspondence: Arti Singh (arti@iastate.edu)

Received: 10 December 2025 | **Revised:** 17 February 2026 | **Accepted:** 26 March 2026

Keywords: extrusion | fractionation | functional foods | gluten-free | high-protein | mung bean | plant-based foods | processing technologies | protein isolation | sustainable food systems

ABSTRACT

Mung bean (*Vigna radiata* (L.) Wilczek) is emerging as a valuable ingredient in modern food systems due to its nutritional benefits, functional versatility, and alignment with plant-based, clean-label, and sustainable food trends. This review highlights recent technological advancements in mung bean processing, covering primary processing steps such as dehulling, sorting, and milling, which enhance product quality and yield. Innovations like optical and sensor-based sorting and roller milling have improved control over quality and mung bean flour particle size, optimizing it for applications in bakery, snacks, and pasta products. Advances in extrusion technology, particularly high- and low-moisture extrusion, have broadened mung bean's usage in plant-based protein, instant noodles, and snacks, making it a key ingredient for high-protein and gluten-free options. Additionally, the development of high-purity protein isolates and concentrates through fractionation supports mung bean's role in functional foods and nutraceuticals. Techniques in protein and starch modification further expand mung bean's applications, enhancing its nutritional and functional properties for novel products across traditional and modern sectors. Mung bean's potential is amplified by rising consumer preferences for health-focused and environmentally sustainable foods. These innovations position mung bean as an essential ingredient in future food solutions, with opportunities for growth in functional foods, clean-label products, and plant-based nutrition markets. This review provides insights into the current advancements and future perspectives, underscoring the mung bean's role in driving value-added food innovations.

1 | Introduction

Mung bean (*Vigna radiata* L. Wilczek) is a food grain legume crop covering over 7 million hectares worldwide (Somta et al. 2022). It is a short-duration crop (70–90 days to maturity) with low input requirements, drought tolerance, and soil nitrogen-fixing ability (R. Nair and Schreinemachers 2020; Somta et al. 2022). It is commonly grown in countries including India, China, Myanmar, Thailand, Africa, Australia, parts of southern Europe, Canada, and the United States (Boddepalli and Singh 2025; R. Nair and Schreinemachers 2020; Sandhu and Singh 2021; Wilbur et al. 2025; Yi-Shen et al. 2018). Its adaptability to various agro-climatic conditions and its role in sustainable agriculture, particularly crop rotation, further emphasize its global significance.

Mung bean is a rich source of easily digestible proteins, dietary fiber, essential minerals, vitamins, and bioactive compounds, making it a vital functional food for enhancing good health (Feng et al. 2023; Karami et al. 2025). It is also highly valued for its rich content of essential amino acids, such as leucine, isoleucine, and lysine, making it an excellent source of protein (Yi-Shen et al. 2018), a wide range of minerals (Jha et al. 2025; Mehta et al. 2021), and low fat (1.3%–2.91%)

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content. Their antioxidant properties, which come from phenolic compounds and flavonoids, further enhance their role in promoting overall health and preventing chronic diseases (Hou et al. 2019). Because of its health benefits and versatility in plant-based diets, it is gaining popularity in Western countries (Somta et al. 2022).

Conventional mung bean processing involves cleaning, grading, conditioning, dehulling, splitting, and milling operations. Dehulling is commonly achieved through water or oil conditioning, followed by abrasion-based milling and separation of husk and splits. While these methods are widely practiced and cost-effective, they often result in variable efficiency, higher losses, and inconsistent product quality. The global demand for mung beans has been steadily increasing, driven by their use in traditional cuisines and modern food products such as plant-based protein isolates, snacks, and ready-to-eat meals (Hou et al. 2019; Tarahi et al. 2024; Yi-Shen et al. 2018). This rising demand has created more trade opportunities, particularly in Asia, where countries like Myanmar and India are leading exporters (Ademe 2023; Diatta et al. 2024; Somta et al. 2022). Additionally, the economic benefits of mung bean cultivation extend beyond direct sales; they also enhance soil health through nitrogen fixation, which decreases the need for chemical fertilizers in subsequent crops (Gong et al. 2024; Pataczek et al. 2018).

The primary objective of this review is to present a comprehensive summary of recent technological advancements in mung bean processing and utilization, with a specific focus on value addition. This review is particularly relevant given the increasing global interest in plant-based proteins and sustainable food systems. Mung beans, known for their nutrient density and environmental friendliness, are attracting considerable attention for their potential role in addressing food security and nutritional challenges. Recent advancements in processing technologies have expanded the ways mung beans can be used, making them a key ingredient in innovative food products such as plant-based proteins, functional foods, and ready-to-eat snacks. Existing reviews on mung bean largely focus on nutrition, protein properties, and health-related applications. In contrast, the present review highlights recent technological advances in mung bean processing and utilization, with an emphasis on milling, dehulling, process optimization, and value addition, thereby addressing a critical gap in the current literature.

2 | Mung Bean Grain Structure, Composition, Physical, and Nutritional Properties

2.1 | Grain Structure

The structure of the mung bean grain contributes to its unique properties, and each grain has three main parts: the seed coat (SC), embryo (EM), and cotyledons (COs). The SC comprises 12.2%–23.5% of the dry weight; the EM makes up 2.3%, and COs account for 76.5%–87.2% (Dahiya et al. 2015; Mohan Naik et al. 2020). Mung bean grains consist of the following five primary components: CO, SC, EM, (Mohan Naik et al. 2020), and embryonic root (ER) (Figure 1). Among these, much of the seed is constituted of the starchy CO and SC, a source of fiber, which consists of approximately 85.6% and 12.1% of the seed, respectively (Mohan Naik et al. 2020). The following sections will summarize the physical and engineering properties of this grain, followed by a discussion of its functional properties in relation to the use of mung beans in the products described in Section 6.

2.2 | Physical and Engineering Properties

Understanding the physical and engineering properties of the mung bean is essential for optimizing its handling, processing, and storage. These properties: including size, shape, density, porosity, bulk density, hardness, and thermal characteristics directly influence the design and efficiency of equipment used in cleaning, grading, dehulling, milling, drying, and packaging. Additionally, they are critical for predicting the behavior of mung beans during storage, particularly in relation to moisture migration, aeration, and spoilage risk. Accurate knowledge of these parameters aids in process engineering, equipment calibration, and the development of value-added products, thereby improving the overall quality and shelf life of mung bean–based foods.

This structural composition influences the grain's physical characteristics and is crucial for postharvest handling, such as seed sorting, processing, and storage. The average dimensions of mung bean grains are approximately 5 mm in length, 3.7 mm in width, and 3.6 mm in thickness, with a geometric mean diameter of about 3.9 mm and sphericity of 0.7 (Dahiya et al. 2015; Ikegwu 2023; Unal et al. 2008). These grains have a 1000-grain mass ranging from 31.4 to 64.6 g, bulk density between 650.0 and 840.0 kg/m^3, and true density from 1230.0 to 1457.0 kg/m^3 (Dahiya et al. 2015; Ikegwu 2023; Unal et al. 2008). The angle of repose varies from 23.7° to 37.5° (Ikegwu 2023; Unal et al. 2008), while the static coefficient of friction is highest on galvanized iron and lowest on stainless steel. Information on selected grain properties is presented in Table 1. Understanding these structural properties is crucial in automating the characterization of mung bean grains for milling and processing (Erkinbaev et al. 2017).

Moisture content significantly influences these properties, with increasing moisture leading to larger grain dimensions, increased true density, porosity, angle of repose, coefficient of friction, and Reynolds number and a reduction in bulk density. With the increase in moisture content, the porosity, angle of repose, terminal velocity, static coefficient of friction, and Reynolds number of mung bean grains increase, and their rupture strength and drag coefficient decrease (Ikegwu 2023; Inekwe et al. 2019; Shahbazi 2015; Unal et al. 2008). Insights into these moisture-dependent characteristics are crucial in optimizing equipment design and processes for harvesting, transporting, and storing mung bean grains, ultimately enhancing their handling and processing efficiency.

Dahiya et al. (2015) comprehensively reviewed the diversity of mung bean grain colors, including shades of green, yellow, black, and brown, primarily due to the pigmentation of their seed. Genetic factors, storage conditions, and compounds like

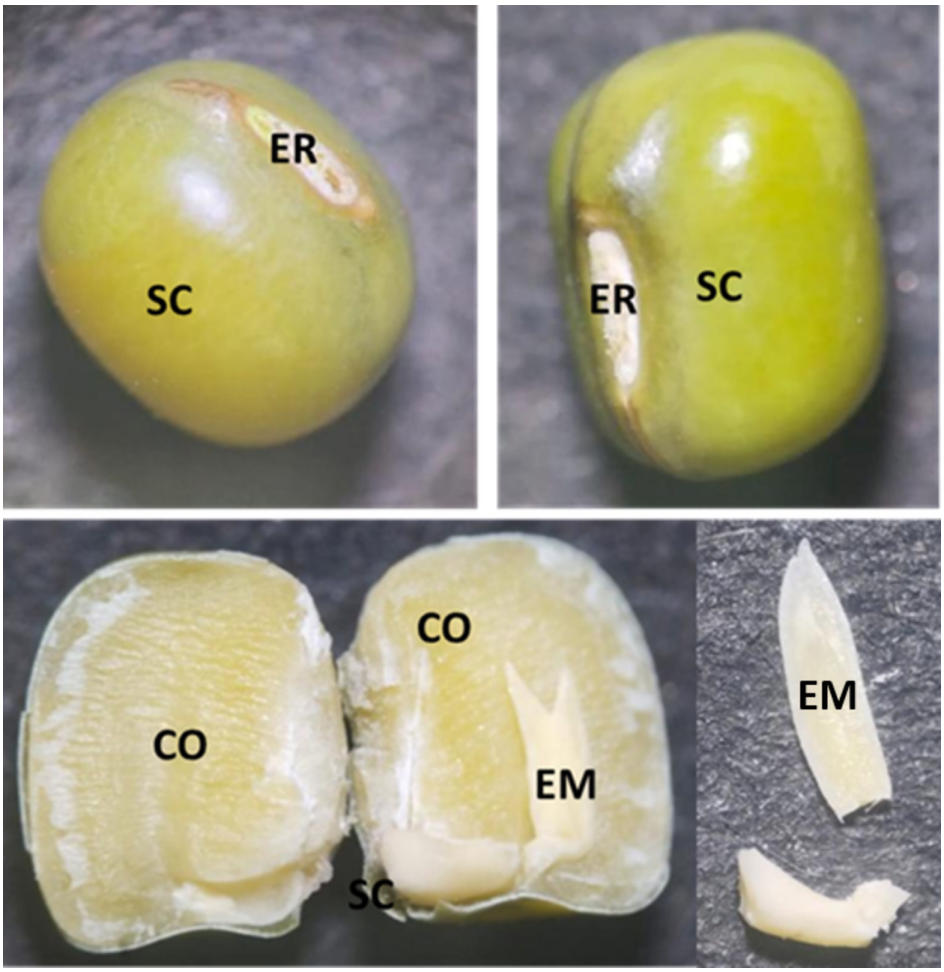


FIGURE 1 | Mung bean grain structure. CO, cotyledon; EM, embryo, ER, embryonic root; SC, seed coat.

polyphenols and carotenoids influence grain color, and changes can occur during processing, particularly due to thermal treatments that cause chlorophyll degradation and Maillard reactions. The lack of studies on specific *L* a* b** color values for mung bean highlights a need for more precise, instrument-based color assessments in future research. The color of mung bean grains influences the appearance of food products made from whole beans, emphasizing its significance in agricultural and culinary contexts.

2.3 | Chemical Composition and Nutritional Properties of Mung Bean

Mung bean is widely recognized for its rich nutritional profile and health-promoting potential, making it a valuable component of both traditional diets and modern functional foods also serving as an alternative to meat (Karami et al. 2025; N. Sehrawat et al. 2021; Nirmala Sehrawat et al. 2023). The chemical composition of mung bean includes high-quality proteins, complex carbohydrates, dietary fiber, and essential micronutrients. It also contains bioactive compounds like polyphenols, flavonoids, and phytic acid, which contribute to its antioxidant and antidiabetic effects (Yi-Shen et al. 2018). Mung bean is low in fat and naturally gluten-free, making it particularly suitable for health-conscious consumers and individuals with celiac disease (Balighi et al. 2024; Taşkın and Savlak 2022). Understanding the chemical and nutritional properties of mung bean is crucial for its application in developing fortified, functional, and therapeutic food products, as well as for improving food security and nutrition outcomes in both developing and developed regions.

Proximate analysis of the whole seed reveals a range of nutritional components, including protein, fat, ash, fiber, and carbohydrate content (Table 2). Carbohydrates form the majority, comprising 62.55%–65.67% of the seed's composition (Ge et al. 2021; Varma et al. 2018). At a moisture content of 4%–10%, the protein content ranges from 15.8% to 26.23% (Ge et al. 2021; Nagrale et al. 2018; Tresina et al. 2014; F. Wang et al. 2021). As noted in Table 2, mung beans provide a good source of fiber, vitamins, and minerals. They also contain phenolic acids and polysaccharides (F. Wang et al. 2021). Methionine, an amino acid of interest in breeding grain legumes, averages 1.26 mg/100 g, with a range of 0.79–1.76 mg/100 g (Krishnan and Jez 2018; Simion 2018; Varma et al. 2018). Linolenic and oleic acids are fatty acids commonly known to impact health, and mung beans contain, on average, 21.17% and 4.47% of each, respectively (Marangoni et al. 2020; Tutunchi et al. 2020; F. Wang et al. 2021). Table 2 provides an overview of some selected nutritional components of mung beans.

TABLE 1 | Dimensional and gravimetric properties of mung bean grain.

Property	Symbol	Unit	Value	References
Moisture range	Mc	% (w.b.)	7.30–22.20	(Dahiya et al. 2015; Ikegwu 2023; Unal et al. 2008)
Dimensional properties				
Grain length	L	mm	4.20–5.90	
Grain width	W	mm	3.10–4.20	
Grain thickness	T	mm	3.00–3.90	
Seed coat thickness*	Tsc	mm	0.06–0.09	
Geometric mean dia.	Dg	mm	3.50–4.30	
Sphericity	ϕ	—	0.58–0.82	
Gravimetric properties				
1000-Grain mass	M1000	g	31.40–64.60	
Bulk density	ρb	$kg\,m^{-3}$	650.00–840.00	
True density	ρt	$kg\,m^{-3}$	1230.00–1457.00	
Porosity	ε	%	30.00–46.60	
Frictional and aero. properties				
Angle of repose	θ	deg (°)	23.70–37.50	(Dahiya et al. 2015; Ikegwu 2023)
Static friction (steel)	μs	—	0.27–0.40	
Terminal velocity	Vt	$m\,s^{-1}$	4.86–7.50	(Choudhary 2020; Ghasemlou et al. 2010; Unal et al. 2008)
Rupture force (Z-axis)	Fr	N	61.20–39.80	

2.4 | Functional Properties

Mung bean exhibits diverse functional properties, making it highly versatile in food systems. Its components have high water and oil holding capacities such as protein isolates can absorb > 3 g water/g protein and ~4 g oil/g protein supporting texture, mouthfeel, and shelf stability (Yi-Shen et al. 2018). Mung bean proteins also show moderate to strong foaming (foam volumes > 80% and stability > 60%) and emulsifying properties, aiding aerated and emulsion-based foods, with certain fractions forming exceptionally stable foams that can outperform traditional proteins (Yang et al. 2023; Yi-Shen et al. 2018). Solubility at neutral pH (60%–70%) allows effective incorporation into beverages and liquid foods. Starch and flour pasting and gelation, supported by amylose and resistant starch content, enhance texture in noodles, gels, and coatings (Tarahi et al. 2025). Sahil Gupta et al. (2018) reported that mung bean has a water absorption of 1.50 g/g, which is comparable with chickpea (1.56 g/g) while lentil (1.79 g/g), navy bean (1.71 g/g), and pinto bean (1.77 g/g) have relatively higher values. Highest water absorption capacity is shown by soybean (3.14 g/g) and black bean (2.35 g/g). Oil holding capacity of lentil (2.57 g/g), pinto (1.47 g/g) and soybean (1.38 g/g) are higher than black and mung bean (1.19 g/g), followed by navy bean (1.01 g/g) and chickpeas (0.62 g/g). Least gelation capacity on the other hand was found to be higher in pinto bean (20% w/v), and mung bean (16% w/v), followed by chickpea (14% w/v), black bean, and lentil (12% w/v).

Pea proteins are dominated by legumin (11S) and vicilin (7S) globulins that exhibit good solubility, emulsifying activity, foaming capacity, and moderate gelation, supporting their use in structured plant-based foods. However, the foaming capacity (56%–70%) and stability (20%–60%) were found to be less than that of mung beans. Residual starch and fiber enhance water-holding capacity, which is higher (3.97–6.81 g/g protein) than that of mung bean (1.0–3.3 g/g). Chickpea proteins, together with high starch and fiber content, also provide good water (3.39 g/g protein) and oil (2.45 g/g protein) holding capacities similar to mung beans, and good emulsion stability, though with lower foaming ability (capacity 37% and stability 25%) than pea and mung bean. Protein–starch interactions contribute to higher paste viscosity and gel strength, favoring thickening and textural applications (Kaczmarek et al. 2025).

Functional properties of dehulled mung bean flour, protein isolate, and starch vary widely. A comprehensive list of the functional properties of different fractions is provided in Table 3.

3 | Advances in Mung Bean Processing Technology

Key operations in mung bean preparation include cleaning, grading or quality assessment, processing preparation (dehulling, splitting, and such), milling, fractionation, and extrusion. The specific sequence of operations depends on the final product requirements. Figure 2 provides a graphical overview of this process and how each stage is connected.

TABLE 2 | Chemical composition and selected nutritional composition components of mung bean whole seed samples including the hull. For consistency, all values have been rounded to one decimal place.

Trait	Range	Citations
Protein	14.6%–32.6%	(Dahiya et al. 2015; Nagrale et al. 2018; Nair et al. 2018; Shrestha et al. 2023; Tresina et al. 2014; Varma et al. 2018; F. Wang et al. 2021)
Fat	1.0%–4.1%	
Ash	2.7%–4.2%	
Fiber	3.1%–4.6%	
Carbohydrate	11.97%–65.67%	
Methionine g/16 g N	0.8–1.8	(Varma et al. 2018)
Potassium mg/100 g	867.0–1685.0	(Nagrale et al. 2018; Nair et al. 2018; Nair et al. 2015)
Calcium mg/100 g	63.0–158.0	
Magnesium mg/100 g	97.0–170.0	
Zinc mg/100 g	0.9–6.2	
Iron mg/100 g	3.5–11.2	
Phosphorus mg/100 g	89.0–517.0	
Selenium mg/kg	0.2–0.9	(Nair et al. 2015)
Sodium mg/100 g	11.1–13.4	
Manganese mg/100 g	1.0–2.0	
Copper mg/100 g	0.8–1.2	
Starch g/100 g	39.5–60.7	(F. Wang et al. 2021)
Water-soluble polysaccharide g/100 g	2.0–3.0	
Oleic acid %	2.7–8.2	
Linolenic acid %	17.8–25.9	

Note: Original values may have been reported with varying levels of precision in the source literature.

3.1 | Advances in Grain Quality Assessment

Evaluating mung bean quality is essential for physical, nutritional, and food safety aspects (Hou et al. 2019; Yi-Shen et al. 2018). Uniform size, shape, and strong mechanical properties improve processing, handling, and storage efficiency (Dahiya et al. 2015). Nutritionally, high protein, vitamin, and mineral content must be assessed to ensure a healthy product. Food safety checks for microbes and toxins safeguard consumers, build trust, and support successful production and marketing.

Erkinbaev et al. (2017) explored the single kernel characterization (SKC) technique as an advanced approach for assessing the physical quality of mung beans, focusing on properties such as diameter, weight, moisture content, and hardness. The study evaluated two mung bean varieties and compared SKC results with traditional assessment methods. The SKC technique showed a strong correlation with laboratory-measured weights ($R = 0.98$) and moderate correlations for true diameter ($R = 0.58–0.7$) and moisture content ($R = 0.92$), validating its reliability. Hardness values measured by SKC also demonstrated consistent relationships with maximum force measurements from the Instron universal testing system, suggesting that SKC is a robust and efficient tool for rapidly assessing the geometrical and mechanical properties of mung beans. The study recommends further refinement of SKC-based techniques for different pulse varieties to optimize quality assessment in industrial environments.

In another study, Kaliramesh et al. (2013) explored the use of near-infrared (NIR) hyperspectral imaging to predict moisture, protein, and starch content in mung beans. Partial least squares regression (PLSR) models outperformed principal components regression (PCR) models, achieving lower mean square errors. Identified wavelength regions (960–980, 1100–1110, 1180–1220, 1320–1360, and 1400–1450 nm) present a strong potential for real-time, inline inspection of these constituents in industrial settings.

Storage of mung beans is often compromised by insect pests like the cowpea weevil (*Callosobruchus maculatus*), which can cause significant quality and quantity losses. Kaliramesh et al. (2013) used NIR hyperspectral imaging to differentiate uninfected and infested mung beans across different developmental stages of *C. maculatus*. Significant wavelengths (1100, 1290, and 1450 nm) were identified using principal component analysis, and classification models such as linear discriminant analysis and quadratic discriminant analysis achieved classification accuracies exceeding 85% for uninfected kernels and over 82% for infested ones. These findings highlight the potential of NIR hyperspectral imaging for the rapid, noninvasive detection of infestations, allowing for the development of multispectral imaging systems in grain processing. Advances in mung bean quality assessment have introduced rapid, nondestructive techniques like SKC and NIR hyperspectral imaging. These tools enhance precision in evaluating physical traits, moisture, and nutrient content, while also enabling early detection of insect infestations. Such innovations improve sorting, milling, and storage efficiency, support food safety, and allow for real-time quality control in industrial processing, making mung bean production more reliable and sustainable.

3.2 | Primary Processing

In preparation for further processing, some additional steps include sorting based on color and quality, along with dehulling. Color sorting technology plays a vital role in grain processing by identifying and removing contaminants such as ergot, fusarium, and mycotoxin-infected grains. This technology not only improves the visual appeal of the final product but also enhances food safety and compliance with stringent regulations (Inamdar and Suresh 2014). Color sorting systems, through their precision and automation, reduce labor costs and increase throughput in milling operations, making them indispensable in modern

TABLE 3 | Summary of selected functional properties of mung bean flour, protein isolate, and starch fraction and isolate. For consistency, all values have been rounded to one decimal place. Original values may have been reported with varying levels of precision in the source literature.

Trait	Flour with hull	Flour dehulled	Protein isolate	Starch isolate	Starch fraction
Functional properties					
Water absorption capacity (g/g)	1.2 [1]	3.2 [2]	3.3 [6], 3.0 [7], 1.0–2.8 [8]	0.8[11]	0.8 [4]
Oil absorption capacity (g/g)	0.6[12]	3.0 [2]	3.0 [6], 4.0 [7], 1–3.4 [8]	0.8[11]	0.8 [4]
Emulsification capacity (%)	27.0[13]	28.8[13]	52.8[11]	32.4[14]	26.5[4]
Emulsion stability (%)	94.6[1]	54.2[14]	51.8 [7]	61.2[14]	21.0[4]
Foaming capacity (v/v)	16.0[15]	29.5[13]	89.7[6]	10.5[16]	11.5[16]
Foaming stability (v/v)	10.0[17]	20.0[17]	80.8[68]	1.5[16]	2.9[16]
Bulk density (g/mL)	0.80 [1]	1.1 [2]	0.4[16]	0.5[16]	0.6 [4]
Swelling index (g/g)	2.1[18]	10.5 [2]	2.1[18]	10.3[18]	2.5 [4]
Least gelation concentration (%w/v)	8.0[19]	8.0[19]	12%[7]	4.0[20]	10.0[20]
Solubility index (%)	20.8[13]	18.6[13]	28.7[13]	0.2[13]	1.6 [4]
Pasting properties					
Pasting temperature (°C)	73.2 [1]	77.9 [2]	74.0[20]	74.0 [3]	77.4 [5]
Peak viscosity (cP)	177.3 [1]	909.0 [2]	2059.0[3]	5622.5[4]	4261.7 [5]
Breakdown viscosity (cP)	71.9[1]	40.0 [2]	501.0[3]	2651.0[4]	1072[5]
Final viscosity (cP)	180.1 [1]	1387.7 [2]	3033.0[3]	3046.0 [3]	4446.0 [4]
Setback viscosity (cP)	74.7[1]	518.7 [2]	1580.0[3]	1739.0[3]	3306.3 [5]
Thermal properties					
Gelatinization onset (°C)	54.0[21]	65.0[21]	56.3[3]	59.2[3]	70.1[5]
Gelatinization peak (°C)	67.0[21]	69.0[21]	67.0[21]	69.0 [3]	72.8[5]
Gelatinization conclusion (°C)	70.0[21]	75.0[21]	79.9[21]	75.0 C [3]	75.8 [5]

Note: References: 1 - (Du et al. 2014), 2 – (Ratnawati et al. 2019), 3 - (Kim et al. 2018), 4 - (Andrabi et al. 2016), 5 - (Phrukwiwattanakul et al. 2014), 6 - (Brishti et al. 2017), 7- (Brishti et al. 2020), 8 - (Li et al. 2010), 9 - (Du et al. 2018), 10 - (Gunathilake et al. 2016), 11 - (Huang et al. 2024), 12 - (Park et al. 2025), 13- (Abdel-Rahman et al. 2008), 14 - (Tian et al. 2025), 15 - (Tarahi et al. 2025), 16 - (Photinam et al. 2025), 17 - (Mehta et al. 2021), 18 - (Kaur et al. 2015), 19 - (Christina Wintersohle et al. 2023), 20 - (Yu et al. 2023), 21 - (Handa et al. 2017).

grain processing (Cha et al. 2025; Tolybayev et al. 2021; Wu et al. 2022).

Dehulling, an essential step, involves the removal of the SC to enhance the nutritional profile and improve product functionality. The SC of mung bean contains antinutritional factors such as phytic acid, polyphenols, and tannins, which impair nutrient bioavailability and contribute to darker-colored final products (Dahiya et al. 2015; Sanaei Nasab et al. 2024). Dehulling improves nutrient absorption and protein functionality, making mung bean more suitable for producing high-quality protein isolates and flours for plant-based foods (Christina Wintersohle et al. 2023). Mung beans are considered "hard-to-dehull" due to the strong bond between the SC and CO. Preconditioning treatments such as drying, soaking, steaming, and tempering have been explored to improve dehulling efficiency (Opoku et al. 2003). Short-term germination (4–48 h) has also been shown to enhance dehulling efficiency while reducing antinutritional factors (C. Wintersohle et al. 2024). Germination for 12–24 h optimizes dehulling while preserving nutritional quality, providing a practical method for improving mung bean flour for plant-based protein applications. Tajoddin et al. (2010) analyzed 10 mung bean cultivars and reported dehulling significantly reduced polyphenol content by 14%–52%, thereby improving the bioavailability of nutrients in mung beans. Studies, such as those by (Pokharel et al. 2024), have confirmed that dehulling is particularly effective in reducing tannin content, making it a crucial step in enhancing the nutritional quality of mung beans for various food applications.

Primary mung bean processing (sorting, cleaning, and dehulling) crucially determines product quality, safety, and functionality. Techniques like color sorting remove defective grains, while dehulling enhances digestibility and reduces antinutrients. Pretreatments such as soaking, drying, and short-term germination further improve efficiency and quality. These advancements enable value-added, health-focused mung bean products, and broader industrial applications.

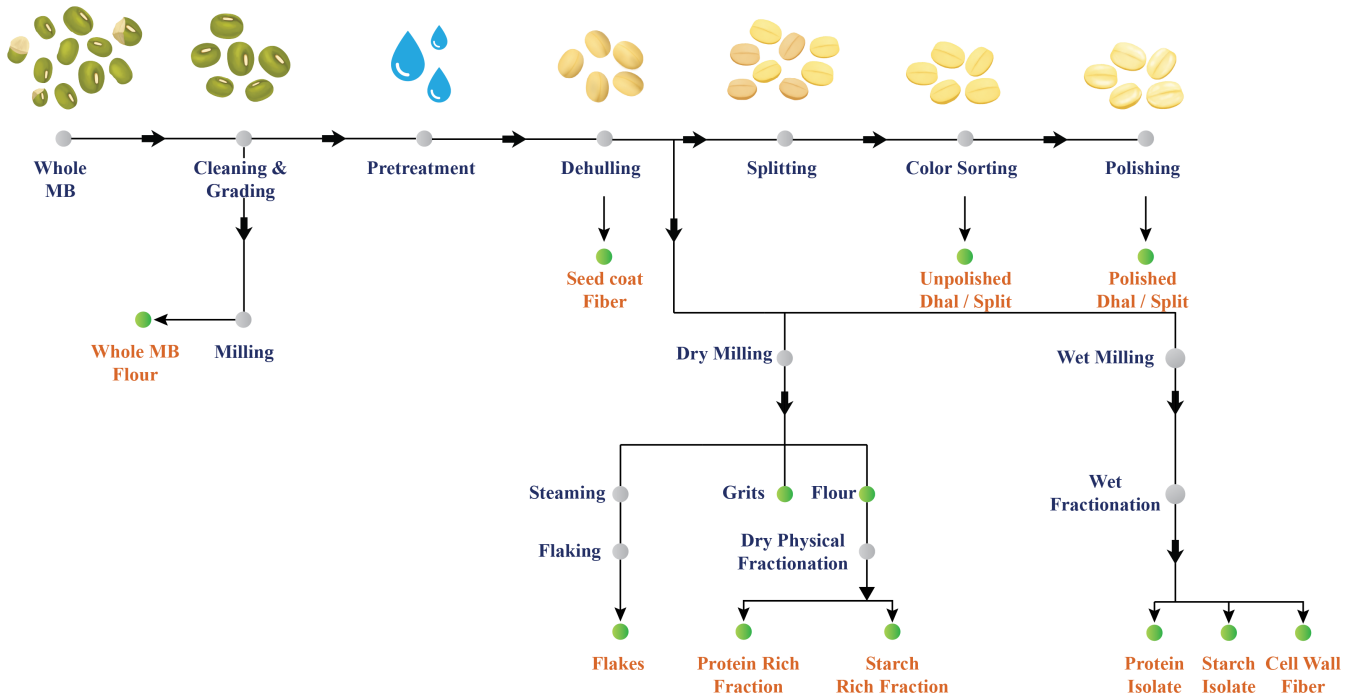


FIGURE 2 | Different processing technologies of mung bean. Lines and arrows indicate the direction of travel for the product/outcome of each step. Green dots indicate potential products, while gray dots indicate processing steps.

3.3 | Milling Techniques

The milling of mung bean shares many objectives with the processing of other pulses, focusing on particle size reduction, separation of botanical components, and inducing physicochemical modifications in the flour (Scanlon et al. 2018). The size reduction process is critical to producing flour or fractions suitable for further applications, including blending with other flours in product development. Successful dehulling results in refined fractions such as dehulled flour, which is often used in high-protein applications, while the SC serves as a valuable source of dietary fiber for animals. Sieving and air-classification techniques are commonly employed to isolate protein-rich fractions from starch-rich fractions, enhancing both the functional and economic value of mung bean ingredients. Milling-induced physicochemical changes, such as starch damage, significantly impact water absorption, a critical factor in the functional performance of mung bean flour for baking and other formulations requiring hydration properties. The degree of starch damage directly influences the texture, stability, and overall quality of the final food product, making this an essential consideration in the milling process (L. Jiang et al. 2025; Niu et al. 2023; Z. Wang et al. 2025).

A study by Yu et al. (2023) explored the effects of different milling techniques on the physicochemical properties of whole-grain mung bean flour, comparing universal grinders, ball mills, and vibration mills. The research revealed that both ball mills and vibration mills significantly reduced particle sizes, resulting in uniform particle distribution, increased specific surface area, and improved water-holding capacity, oil-holding capacity, and swelling power. These findings underline the importance of comminution techniques in enhancing the structural and functional properties of mung bean flour. Ball milling, in particular, has been highlighted as an efficient method for particle size reduction. Ahmed et al. (2025) demonstrated that high-energy ball milling effectively converts mung bean seeds into nanoflour with particle sizes in the range of 222–273 nm. Ball size influenced particle morphology, surface characteristics, thermal behavior, and rheological properties, while ball size combinations showed mixed effects on particle size. Haryanto et al. (2020) demonstrated that ball milling conditions could be optimized to achieve fine particle sizes, emphasizing its potential for tailored food processing applications. The roller milling method has also been employed to process mung beans, particularly in efforts to enhance grain fractions for food ingredient applications.

Sakhare et al. (2014) showed that increasing conditioning moisture from 10% to 16% led to a decrease in flour yield, while roller milling produced protein- and fiber-rich fractions suitable for incorporation into bakery and traditional food products. This method has proven effective in improving the nutritional value of the resulting flour while maintaining its functional properties. Further innovations in roller milling have explored the production of semolina from mung bean to improve its nutritional profile and functionality. A three-pass roller milling system designed specifically for mung beans was used to optimize the separation of semolina from mung bean splits, with the resulting semolina demonstrating enhanced protein content and quality suitable for diverse food applications (Jyotsna et al. 2014). Tulse et al. (2014) explored roller milling of multigrain blends consisting of wheat, mung beans, and barley in various ratios, demonstrating that roller milling can effectively enhance the nutritional quality of flour while maintaining desirable properties for bread production.

Schlangen et al. (2022) investigated a hybrid milling approach, combining pin and impact milling for mung beans. This

technique allowed for efficient particle size reduction and resulted in high-protein fractions through air classification. The study emphasized the benefits of combining different milling technologies to improve flour quality and functionality, particularly for the production of protein-rich fractions with excellent gel-forming properties. Indira and Bhattacharya (2006) examined the grinding characteristics of legumes, including mung bean, using hammer milling, revealing that the intrinsic properties of legumes, such as internal structure and thickness, influence their susceptibility to grinding. This finding is crucial for optimizing energy efficiency and grinding performance in mung bean milling.

The reviewed studies collectively highlight the diverse milling techniques applied to mung bean processing, each offering distinct advantages in terms of flour quality, functionality, and nutritional value. Ball milling and vibration milling stand out for achieving uniform particle size and enhancing water-holding and swelling properties, making them particularly effective for applications requiring high hydration. In contrast, roller milling, especially with moisture conditioning, supports fractionation into protein- and fiber-rich components, benefiting bakery and traditional products, though it may reduce overall flour yield. Hybrid milling approaches further enhance protein concentration and functionality, particularly gel formation, showing promise for high-protein food formulations. Overall, a comparative view suggests that tailored milling strategies, possibly integrating techniques, can optimize mung bean flour for specific end uses by balancing yield, nutrient concentration, and functional performance.

3.4 | Fractionation

The fractionation of mung beans has also garnered significant attention. Dry fractionation, a sustainable alternative to wet fractionation, has emerged as a cost-effective method for producing functional protein concentrates (Schlangen et al. 2023, 2022; Skylas et al. 2024, 2025). The exploration of dry fractionation as an alternative to wet fractionation highlights its sustainability and energy efficiency, particularly in protein extraction processes. Schutyser et al. (2015) demonstrated that dry fractionation produces 55.8 g of protein per megajoule (MJ) of energy, while wet methods yield only 14.6 g per MJ. Despite this, dry fractionation typically results in lower protein purity. In response, hybrid fractionation approaches have been investigated, offering a middle ground between energy efficiency and purity, producing 29.1 g of protein per MJ. By optimizing milling conditions and selecting appropriate varieties, dry fractionation can achieve higher protein purity, making it suitable for applications such as high-protein beverages and structured solid foods. Schlangen et al. (2023) further expanded the understanding of dry fractionation by investigating its effect on mung bean proteins and their response to transglutaminase crosslinking. The study compared four protein fractions: a fine fraction obtained through dry milling and air classification, a heated fine fraction, a wet fraction, and a commercial protein isolate. Results showed that transglutaminase significantly altered the rheological properties of the fine and wet fractions, but the commercial isolate exhibited minimal changes. The study emphasizes that protein functionality and susceptibility to crosslinking are closely tied to the structural states resulting from different fractionation methods.

Yang et al. (2023) developed a systematic approach to mung bean protein fractionation, combining dry and wet techniques based on solubility at different pH levels and temperatures. The resulting protein fractions, including colloids, globulin-rich, and albumin-rich fractions, were evaluated for their interfacial and foam-stabilizing properties. The albumin-rich fraction exhibited superior foaming properties due to its higher surface density, while protein colloids showed enhanced foam stability. This research highlights the potential of mung bean proteins as functional ingredients, particularly in food products that require foaming and emulsification properties. Krishnappa et al. (2017) explored the antioxidant activity and phenolic acid composition of mung bean exudates, husks, and germinated seeds. Germination increased polyphenol and flavonoid content, with sinapic acid identified as the most abundant phenolic compound. Exudates and husks from germinated seeds exhibited strong antioxidant and antimicrobial activities, suggesting their potential use as natural preservatives in food products. This study was the first to report on the antioxidant properties of mung bean exudates, adding to the functional profile of mung beans in nutraceuticals and functional foods.

In addition to protein fractionation, Schlangen et al. (2022) studied the dry fractionation of mung bean flour, demonstrating the potential to produce protein-rich fractions with varying water-holding capacities and gel-forming abilities. Mung bean flour showed a positive correlation between protein content and water-holding capacity. Zhu et al. (2020) further optimized dry separation techniques, achieving 84% protein separation efficiency and a protein purity of 63%, demonstrating the potential for dry fractionated protein concentrates to have superior antioxidant capacity compared to wet fractionation isolates. Recent advances in mung bean fractionation highlight the shift towards dry and hybrid methods as energy-efficient and sustainable alternatives to traditional wet processes. While dry fractionation offers higher energy efficiency, hybrid approaches balance energy savings with improved protein purity. These methods produce protein-rich fractions with desirable functional properties such as water-holding capacity, gel formation, and foaming ability, making them suitable for various food applications. Additionally, valorization of by-products like husks and exudates for their antioxidant and antimicrobial properties adds functional value.

Overall, optimized fractionation techniques enhance mung bean's potential as a sustainable source of functional proteins and nutraceutical ingredients. Advancements in the milling and fractionation of mung bean have demonstrated significant potential for enhancing both the nutritional value and functional properties of ingredients derived from mung bean. Innovative milling techniques, such as ball milling, roller milling, and hybrid methods, have optimized the production of protein-rich and fiber-rich fractions. Additionally, dry fractionation presents a sustainable and efficient alternative to traditional wet methods for generating high-quality protein concentrates. These advancements pave the way for incorporating mung bean into a

variety of food applications, ranging from high-protein products to functional foods, thereby contributing to a more nutritious and sustainable food system.

3.5 | Extrusion Processing

Extrusion technology has become a cornerstone of modern food processing, particularly in the production of instant foods and ready-to-eat snacks, offering both efficiency and versatility (Kolawole et al. 2025). It facilitates the development of food products with enhanced nutritional profiles and desirable functional properties, meeting the growing consumer demand for convenient and nutritious alternatives (Abilmazhinov et al. 2023; Dendegh et al. 2022; Pismag et al. 2023). Advances in extrusion have broadened its use in snacks, protein-rich, and gluten-free foods, transforming raw materials through mechanical shear and thermal energy into expanded, textured, and shaped products for cereals, snacks, and plant-based alternatives. Bozdogan et al. (2024) investigated the effect of mung bean flour substitution in corn semolina-based extruded snacks. Increasing the mung bean flour content resulted in a reduced expansion ratio, crispiness, and starch digestibility, while enhancing texture and microstructure, thereby creating a more organized structure. The optimal extrusion conditions included a barrel temperature of 143°C, 16% feed moisture, and 40% mung bean flour, which produced snacks with lower starch digestibility. Azih et al. (2024) optimized extrusion conditions for mung bean snacks, examining the impact of temperature, screw speed, and feed moisture on various properties such as protein content, expansion ratio, bulk density, and hardness. Their study found that higher temperature and screw speed increased expansion and water absorption but decreased bulk density and hardness. The optimal conditions (75.59°C, 142.41 rpm, 55.74% moisture) produced snacks rich in essential amino acids with favorable sensory attributes, particularly taste.

Singh et al. (2024) studied extrusion conditions for dehulled barley-mung bean snacks and found that lower feed moisture and higher barrel temperature led to improved expansion ratio and reduced bulk density. Increased screw speed and barrel temperature enhanced water solubility, while feed moisture increased hardness. Structural and molecular changes were observed through scanning electron microscope (SEM) and Fourier transform infrared spectroscopy (FTIR) analyses, indicating the potential for optimized extrusion conditions to produce functional snacks with improved nutritional quality. Additionally, Sumardiono et al. (2021) created rice analog using a formula containing mung bean flour and found it to be preferred by panelists due to its higher sago starch and skim milk content.

Furthermore, Nguyen and Songsermpong (2023) explored the application of microwave drying in conjunction with extrusion for mung bean vermicelli production, significantly reducing rehydration time while improving the product's sensory properties. This integration of advanced drying techniques with extrusion showcases the potential for innovation in instant food production. Lastly, drum drying has also been applied in gluten-free formulations, as demonstrated by Taşkın and Savlak (2022), who optimized the production of instant fermented tarhana soup using mung bean flour. Their study revealed how drum drying parameters, such as feed moisture, drum speed, and steam pressure, impact the functional properties of the final product, emphasizing the importance of process optimization in achieving high-quality, nutritious instant foods.

The reviewed studies collectively underscore the versatility and potential of mung bean flour in extrusion-based food applications. While increasing mung bean content in extruded snacks may reduce expansion and crispiness, it improves structural integrity and nutritional properties, including amino acid composition and protein digestibility. Optimization of extrusion variables, temperature, screw speed, and feed moisture emerges as a key factor in tailoring textural and functional attributes of snacks, rice analogs, and plant-based proteins. Additionally, integrating technologies like microwave and drum drying further enhances product quality and shelf stability. Overall, these innovations demonstrate that mung bean is a promising ingredient for developing functional, high-protein, gluten-free, and consumer-acceptable extruded and ready-to-eat food products.

3.6 | Mung Bean–Based Protein Concentrate and Isolate Production

Protein concentrates and isolates are highly refined forms of protein derived from various plant and animal sources, widely used in food formulations to enhance nutritional and functional properties. Protein concentrates typically contain 60%–80% protein, while isolates contain over 90%, making them valuable for high-protein diets, sports nutrition, and plant-based food applications. These proteins are extracted through methods such as alkaline solubilization, isoelectric precipitation, salt extraction, and dry fractionation, each influencing the final product's yield, purity, and functional characteristics. Among plant sources, mung bean has gained increasing attention due to its high protein content and desirable techno-functional properties, making it a promising raw material for producing both protein concentrates and isolates in the development of functional and health-oriented food products. The extraction process for isolated mung bean protein was first described in publications as early as 1977, yielding a final product with a protein content of 92% (Thompson 1977). In this method, Thompson used an extraction at pH 9 and 25°C for 20 min, with a flour-to-solvent ratio of 1:15, followed by precipitation at a pH of 4. Because these initial studies, numerous modifications have been explored to reduce extraction costs, alter the properties of the final protein isolate, and improve protein yield. Optimization studies have provided insights into ideal extraction parameters. M. Wang et al. (2011) identified optimal conditions at 31.74°C, a liquid ratio of 10%, an extraction pH of 8.97, a settlement pH of 4.4, and an extraction duration of 33.24 min. Increasing the water ratio from 8% to 10% improved protein yield, but yields declined beyond 10%. Similarly, protein yield increased as extraction temperatures rose from 20°C to 31.74°C but decreased at temperatures above 31.74°C (M. Wang et al. 2011). The extraction pH range of 7–9 showed a steady increase in yield, while settlement pH levels between 4.2 and 4.6 resulted in a sharp rise in yield. Regarding extraction time, yields increased between 20 and 30 min, followed by a gradual decline for durations longer than 30 min (M. Wang et al. 2011).

After extraction from a solution at pH 4.5, the protein curd can be dried using various methods, including freeze-drying, spray-drying, or oven-drying (Brishti et al. 2017). Brishti et al. (2020) found that freeze-dried isolates had the highest protein content among the three methods. However, the aspartic and glutamic acid contents were comparable across all drying methods (Brishti et al. 2021). These studies have evaluated the optimal extraction procedure for increasing protein isolate yield from mung bean using alkaline methods. In addition to extraction via alkaline/isoelectric, there are two other methods of separation that have been studied in mung bean: salt extraction and air separation.

Micellization, also known as salt extraction, reduces phytic acid content while increasing protein content when used for mung bean protein extraction (Rahma et al. 2000). Ratnaningsih and Songsermpong (2021) investigated the effects of different salts and acids on protein extraction. Citric acid resulted in the highest protein yield at 80.33 g/100 g, while $MgSO_4$ produced a protein yield of 78.61 g/100 g. Among the functional properties, $MgSO_4$ extraction showed the highest water-holding and foaming capacities, whereas $CaCl_2$ exhibited greater foaming stability (Ratnaningsih and Songsermpong 2021). These studies provide options for extraction that can be used depending on desired properties needed for the end-product.

Another separation method is air or dry separation. Zhu et al. (2020) tested multiple settings for air separation to optimize protein extraction from mung bean flour. The highest protein purity and yield achieved were 63.2% and 31.9%, respectively (Zhu et al. 2020). In addition to various extraction methods, there are differences due to the mung bean variety used. The functional properties of isolated mung bean protein, including water absorption capacity, oil absorption capacity, foaming capacity, foam stability, emulsifying activity, and protein solubility, vary due to differences in varieties (Li et al. 2010).

Y. Wang et al. (2024) investigated how endogenous proteases in mung beans affect protein yield during aqueous processing. Their findings revealed that certain proteases degrade protein structures, lowering yield and purity. Controlling protease activity during processing could significantly improve extraction efficiency, making mung bean protein more commercially viable for food manufacturers. Alkaline extraction remains the most widely studied, offering high protein purity but requiring careful control of pH, temperature, and extraction time to prevent protein degradation. Salt extraction shows promise for improving functional attributes like foaming and water-holding capacity, though protein yields are slightly lower. Dry fractionation, while energy-efficient and cost-effective, generally results in lower protein purity but holds potential when combined with hybrid techniques. Notably, varietal differences and endogenous protease activity emerge as key factors influencing extraction efficiency and quality.

3.7 | Mung Bean Starch Concentrate and Isolate

Research on mung bean starch isolation and processing adds another dimension to the legume's functional potential. Chang et al. (2006) showed that mung bean starch prepared with lactic acid fermentation solution exhibited lower pasting viscosity and higher gelatinization temperature compared to other isolation methods, making it suitable for starch noodle production. Liu et al. (2020) found that germination increased mung bean starch crystallinity, altering its solubility, swelling power, and pasting properties, which are crucial for food applications. Further studies by Yao et al. (2019) and K. Zhang, Dai, et al. (2019) focused on mung bean starch's low glycemic index potential and the mechanochemical effects of grinding on starch properties. Cooking mung bean starch reduced resistant starch content but retained slowly digestible starch, making it suitable for low-glycemic index applications. Additionally, grinding improved starch solubility and swelling power, offering opportunities to enhance starch quality through mechanochemical methods. Together, these findings underscore mung bean's versatility as a sustainable source of functional proteins and starch for food applications.

3.8 | Processing Modifications Targeting Plant-Based Protein Alternatives

Further research by De Angelis et al. (2023) explored the rheological properties of dry-fractionated mung bean protein in high-moisture extrusion cooking. Their study highlighted the impact of temperature and moisture on the dynamic modulus and textural characteristics such as hardness and chewiness. Higher temperatures facilitated starch gelatinization and protein gelation, which are crucial for developing plant-based protein alternatives with improved texture and mouthfeel. These findings indicate the importance of optimizing processing conditions for achieving the desired texture in plant-based protein products. Seetapan et al. (2023) developed high moisture protein alternatives by blending mung bean protein isolate and mung bean flour with varying portions of mung bean flour (10%, 20%, and 30%) using high moisture extrusion and die texturization techniques. Because pure mung bean protein isolate could not be extruded or texturized, the addition of mung bean flour improved the extrudability and texturization of the high-moisture protein alternatives. Rheological analysis showed that mung bean protein–flour blends had lower storage and loss moduli, indicating better flow, while extrudates displayed anisotropic layering and, at higher flour content, a notable phase separation leading to reduced texture. Overall, the blend of mung bean protein isolate and mung bean flour demonstrates potential for creating mung bean–based high-moisture protein alternatives with customized texture properties.

The structuring of plant-based protein alternatives is further refined through various processing techniques. Baig et al. (2024) utilized response surface methodology to optimize the concentration of starch, protein, and oil in plant-based protein alternatives made from mung bean protein isolate and pea protein isolate. They found that starch played a significant role in enhancing the protein matrix, improving the texture of the protein alternatives. Additionally, Y. Wang et al. (2024) explored the freeze–thaw stability and thermal gel properties of mung bean protein-based emulsions. Their study demonstrated that pH-shifting and transglutaminase cross-linking improved the emulsifying activity and gel stability, offering potential for plant-based egg substitutes with properties similar to real egg liquids.

High-moisture extrusion proved essential for achieving meat-like textures, with the addition of mung bean flour enhancing extrudability and reducing brittleness. Comparatively, structuring was more effective when blends or functional additives like starch and oil were used. Overall, mung bean protein shows versatility but performs best when combined with other components or modified through advanced processing to achieve desired functional attributes.

4 | Mung Bean Treatment and Modification for Functionality

Recent research has made substantial strides in modifying mung bean grains and flour to improve their functional, structural, and nutritional properties. These advancements have expanded the application of mung beans in various food systems, positioning them as a versatile and functional ingredient. This section explores key developments in mung bean protein and starch modification.

4.1 | Protein Modification

Protein modification involves altering the molecular structure or chemical groups of proteins using various methods to enhance their techno-functional properties. By modifying proteins, they can be transformed into multifunctional ingredients suitable for a wide range of food products. Over the past few years, numerous protein isolates have undergone modification through different techniques, leading to significant improvements in their functional characteristics and increasing their industrial applicability. Various modification techniques have been employed to improve the functional properties of food proteins, leading to increased industrial applications and greater use of underutilized protein sources. These techniques can generally be categorized into three main groups: physical, chemical, and biological. Among them, physical methods have gained the most popularity due to their environmentally friendly nature, absence of chemical residues, continuous operation, and reliability and safety (Basak and Annapure 2022). The functional properties of proteins are influenced by their physicochemical characteristics, interactions with both protein and nonprotein components, and the environmental conditions of the food system. These properties play a crucial role in determining how food behaves during preparation, processing, storage, and consumption, while also contributing to the overall quality and sensory attributes of the food (J. Liu et al. 2012). Mung bean protein is gaining attention for its functional properties, especially its water-holding capacity, gelation, and emulsification potential. Various studies have explored innovative techniques to enhance these properties, enabling the use of mung bean proteins in a wide array of food products. Below is a synthesis of the latest research regarding mung bean protein modification.

Jeong and Cho (2024) conducted an in-depth study on mung bean protein isolate, focusing on its water-holding capacity and gelation properties through pH-shifting techniques. Their results demonstrated that treating mung bean protein isolate under alkaline conditions at pH 12 significantly enhanced its functionality. The water-holding capacity increased from 1.56 to 4.81 g/g, and the least gelation concentration dropped from 22% to 15%. These improvements were attributed to the unfolding of globular proteins under alkaline conditions, exposing hydrophilic amino acids, which increased water absorption and enhanced gel formation. In contrast, acidic pH-shifting rendered the protein structure more rigid, diminishing its water-holding and gelation properties. This research underscores that pH manipulation is a promising approach for improving mung bean proteins' functional properties, particularly in food products requiring superior water retention and gel formation. In another innovative approach, Hadidi et al. (2021) explored microwave-assisted phosphorylation as a technique for modifying mung bean protein. Phosphorylation is known to enhance protein solubility, emulsifying ability, and water-holding capacity. The optimal phosphorylation conditions, STP/protein ratio of 0.063 g/g, microwave power of 590 W, microwave time of 155 s, and pH of 7.8, resulted in a maximum phosphorylation degree of 3.27%. The microwave-assisted method provided a fast and efficient way to enhance these properties, resulting in a modified protein with improved water and oil-binding capacities, as well as enhanced emulsifying and foaming characteristics. This approach holds potential for food and pharmaceutical applications and shows promise for modifying other plant-based proteins.

Vijayan et al. (2024) demonstrated that using microbial transglutaminase to cross-link mung bean protein isolate improved both gelation and emulsification properties, making the protein ideal for use in plant-based seafood alternatives. The treated samples exhibited a threefold increase in water-holding capacity (3.77 ± 0.06 g/g) compared to the control (1.24 ± 0.02 g/g), alongside a 15% decrease in zeta potential and an increase in emulsifying activity index from 3.79 ± 0.01 m^2/g (control) to 4.519 ± 0.004 m^2/g. The cross-linked protein exhibited enhanced texture and stability, providing a promising ingredient for plant-based products that mimic seafood textures. R.-X. Wang, Li, et al. (2023) examined the effects of transglutaminase treatment (particularly at 30 U/g) on the structural and gelation properties of mung bean protein gel. By analyzing surface hydrophobicity, free sulfhydryl groups, and gelation properties through rheological measurements and texture analysis, they discovered that transglutaminase treatment significantly reduced surface hydrophobicity and free sulfhydryl groups, forming new protein networks through cross-linking. This led to a more compact gel network with enhanced gelation properties, reflected in improved hardness, chewiness, cohesiveness, and water-holding capacity. However, excessive transglutaminase concentrations (> 30 U/g) negatively affected the uniformity and density of the gel structure. This study confirmed that transglutaminase treatment effectively enhances mung bean protein gels for various food applications.

In a study by Rahman and Lamsal (2023), high-power sonication (250 J/mL for 2 min) and atmospheric cold plasma (80 kV for 5 min) were used to modify mung bean protein isolate gels. Atmospheric cold plasma treatment improved the firmness and structural integrity of the gels, making them suitable for products that require structural robustness. Meanwhile, high-power sonication enhanced the texture and mouthfeel, making the gels more suitable for creamy or spreadable products. These results demonstrate how advanced processing techniques can tailor mung bean protein gels for diverse food applications.

Diao et al. (2022) modified mung bean proteins through hydrothermal treatment to enhance gel properties and assessed the impact on wheat noodle quality. The optimal conditions were identified as 105°C for 30 min with a moisture content of 50%, resulting in improved water absorption and noodle quality. Hydrothermal treatment enhanced the gel properties by increasing protein solubility and forming water-stable gels, making this approach practical for improving noodle production. In research by Limpisophon et al. (2024), the combination of alkaline treatment (0.3% and 3.5% Na_2CO_3) and heat (40°C and 70°C) was used to develop plant-based emulsion gels for protein alternatives. These treatments reduced the zeta potential of protein suspensions from −9 to −19 mV, altered protein conformation, and resulted in smaller particle sizes (426–166 μm), improving the emulsifying activity index (6.34–10.89 m^2/g) and stability coefficient (43%–96%). These findings suggest that combining alkaline and heat treatments significantly enhances mung bean protein's potential for use in plant-based emulsions.

Mung bean protein modification effectively showcases diverse and innovative strategies, ranging from pH shifting, enzymatic cross-linking, and phosphorylation to physical treatments like sonication and cold plasma that significantly enhance its functional properties. Each method targets specific techno-functional traits such as gelation, emulsification, solubility, and water/oil-binding capacity, aligning the modified protein with various food applications. Comparatively, alkaline pH-shifting and enzymatic treatments like transglutaminase offer the most substantial improvements in gel strength and water-holding. In contrast, physical methods such as microwave-assisted phosphorylation and cold plasma provide versatile, rapid, and cleaner alternatives with scalable potential.

4.2 | Starch Modification

Starch is a homopolysaccharide composed of glucose units connected by glycosidic bonds. This biopolymer is valued for its low cost, biodegradability, renewability, and abundant availability. However, native starches often lack the desired properties for optimal use in food products, so they are typically modified to enhance their functionality before being applied in processed foods. Starch modification can be achieved through chemical, physical, or enzymatic methods.

Mung bean starch, with its distinct physicochemical characteristics, presents a promising option for modification, expanding its potential applications in both food and packaging industries. A related study by Kumari et al. (2022) explored the fabrication of mung bean starch nanocrystals through acid hydrolysis. Starch nanocrystals have unique functional properties, including improved flowability and the ability to encapsulate bioactive compounds. The mung bean starch nanocrystals produced in the study showed favorable shear-thinning behavior, making them suitable for beverages and sauces. These findings emphasize the potential of mung bean starch nanocrystals as functional ingredients in various food formulations.

Duyen et al. (2020) combined citric acid treatment with heat-moisture and annealing techniques to modify mung bean starch, increasing its resistant starch content. These combined treatments increased the resistant starch content (41.1%), making the modified mung bean starch suitable for functional foods aimed at consumers seeking lower glycemic index products. Liang et al. (2021) investigated the effects of continuous and repeated dry heat treatments on mung bean starch at 130°C for durations ranging from 3 to 18 h, observing significant structural and physicochemical changes. Dry heat treatment decreased molecular weight, amylose content, swelling power, and viscosity, while solubility and thermal enthalpy values increased. The content of slowly digestible and resistant starch increased during the initial treatment stages, indicating potential health benefits, such as lower glycemic index values. These findings suggest that dry heat treatment is an effective method for modifying mung bean starch for food industry applications.

N. Wang, Dong, et al. (2023) examined the effects of high hydrostatic pressure treatment on mung bean starch, highlighting its potential to enhance cationic starch quality. High hydrostatic pressure treatment at 500 MPa and 40°C facilitated water and etherifying agents' penetration into starch granules, resulting in significant structural changes. The physicochemical properties of mung bean starch, including solubility, swelling power, and viscosity, improved, suggesting that combining high hydrostatic pressure with etherification can enhance starch modification for use in various industries.

Jiang et al. (2015) investigated the rheological properties of mung bean starch water suspensions subjected to high hydrostatic pressure treatments at 120, 240, 360, 480, and 600 MPa for 30 min. The storage and loss moduli of the high hydrostatic pressure-treated starch increased with pressure, indicating enhanced rigidity and viscoelasticity, which led to weak gel formation. The application of high hydrostatic pressure resulted in structural changes in starch granules, altering their rheological characteristics, which could have industrial applications in food processing. Liu et al. (2021) compared the effects of high hydrostatic pressure processing at levels of 300, 450, and 600 MPa on mung bean flour and mung bean starch, revealing significant differences in their physicochemical properties. High hydrostatic pressure-treated mung bean flour formed amylose-lipid complexes, enhancing gel network cross-linking, while mung bean starch showed more pronounced gelatinization. This research highlights the potential of high hydrostatic pressure as a nonthermal processing technique for modifying legume flour for diverse food applications.

Zhao et al. (2020) investigated the effects of repeated and continuous heat-moisture treatments on mung bean starch, finding that repeated heat-moisture treatment was more effective in enhancing water solubility, swelling power, and pasting properties, while preserving the starch's original crystalline structure. These findings suggest that repeated heat-moisture treatment is an effective approach for enhancing the functional properties of mung bean starch for food applications. In a study by Castanha et al. (2019), the effects of ionizing radiation utilizing doses up to 5 kGy on mung bean starch and grains were investigated, revealing significant changes in functional properties, including reduced cooking time and increased water absorption. However, higher radiation doses negatively affected the germination capacity of mung beans, suggesting potential trade-offs in processing applications.

Mung bean starch can be effectively modified using chemical, physical, and combined methods to enhance its functional properties. Acid hydrolysis yields starch nanocrystals ideal for flow-sensitive foods, while citric acid and dry heat increase resistant starch, suiting low-glycemic applications. High hydrostatic pressure enhances solubility and structure without damaging granules and works well in conjunction with chemical modifications. Repeated heat-moisture treatments enhance pasting and water solubility while maintaining crystallinity. Although ionizing radiation improves functionality, it may affect germination. Overall, mung bean starch is highly versatile, with each method offering targeted benefits for specific food applications.

4.3 | Nutritional Modification

Mung beans' nutritional profile, especially their protein and starch content, makes them an excellent candidate for various modifications aimed at enhancing health benefits and expanding their functional applications. For instance, Lu et al. (2021) addressed the challenge of enhancing lutein's solubility and stability by encapsulating it within a matrix composed of sodium caseinate and acetylated mung bean starch. This encapsulation significantly increased lutein's resistance to heat and light, thereby expanding its use in food products that undergo thermal processing. This research highlights the potential of mung bean starch as an effective encapsulation material for sensitive bioactive compounds.

Chen et al. (2022) investigated the extraction of mung bean skin polysaccharides using various alkali concentrations and compared the results with those obtained from traditional hot-water extraction methods. The study found that alkali-extracted polysaccharides exhibited better antioxidant activity and thermal stability, opening up possibilities for their application in functional foods and nutraceuticals. Chauhan et al. (2024) examined how various cooking methods affect the resistant starch content and glycemic index of mung beans. The study concluded that steaming mung beans after germination, followed by cold storage, resulted in the highest resistant starch content and the lowest glycemic index. This cooking method provides practical insights into maximizing the health benefits of mung beans, particularly for individuals seeking to manage their blood sugar levels.

Padmashree et al. (2016) studied the effects of infrared processing on mung bean seeds, with a focus on water absorption, nutrient retention, and the reduction of antinutritional factors. The findings indicated that infrared treatment significantly increased water absorption, enhanced protein, carbohydrate, and mineral retention, while reducing antinutritional factors, thereby improving protein digestibility. S. Zhang et al. (2022) investigated the interaction mechanisms between mung bean protein and polyphenols in aqueous solutions under various heat treatment conditions. Through fluorescence spectroscopy, Fourier transform near-infrared (FT-IR), and particle size analysis, the research revealed that the binding between mung bean globulin and polyphenols occurred primarily through static quenching mechanisms, driven largely by hydrophobic interactions. Additionally, the study demonstrated that the inclusion of polyphenols had a positive effect on the secondary structure of mung bean globulin, thereby enhancing the thermal stability of the complexes compared to globulin alone. The heat-treated complexes exhibited stronger interactions with mung bean globulin, resulting in a more stable structure posttreatment. These findings offer valuable insights into the binding mechanisms between mung bean proteins and polyphenols, contributing to the advancement of mung bean processing and food production methods.

Nutritional modifications in mung bean effectively enhance its health benefits and functionality. Techniques like starch-based encapsulation improve bioactive stability, while alkali extraction boosts antioxidant-rich polysaccharides. Cooking methods such as germination followed by steaming and cold storage increase resistant starch and lower glycemic index. Infrared treatment enhances nutrient retention and protein digestibility. Additionally, protein–polyphenol interactions improve thermal stability and structure.

5 | Utilization of Mung Beans in Food Products

Mung beans have been utilized in a wide range of applications, from traditional culinary uses to more innovative approaches (Figure 3). The mung bean can be used in a variety of products, including bread, pasta, noodles, cakes, cookies, biscuits, and other extruded foods (Table 4). More innovative approaches involve using mung beans as an alternative to plant-based protein options, packaging films, and beverages. Because of their strong nutritional qualities, mung beans have also been applied in nutraceuticals and functional foods.

5.1 | Traditional Food Applications

Mung bean has long been a cornerstone of traditional cuisines across the globe, with its versatility and nutritional value making it particularly prominent in Asian and African culinary traditions (Ong et al. 2023; Petruzzello 2023). In Asian countries, such as India and China, mung bean is traditionally consumed with rice to counterbalance the lysine deficiency found in cereals (Tarahi et al. 2024). These small green legumes are transformed through various processing methods, enhancing their nutritional profile and expanding their culinary applications. Soups made with instant mung bean powder are

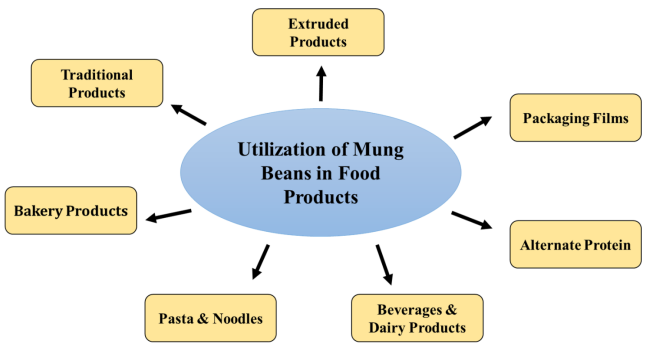


FIGURE 3 | Utilization of mung beans in different food products.

TABLE 4 | Mung bean utilization in bakery and pasta products.

Product category	Processing modification	MB form used	Functional properties	Product outcomes	Citations
Bakery products	• Incorporated into dough • Fortification with MBF • Fortification with wheat flour	• MBF • MBPI • EMBF	+ H_2O absorption + Protein content + Dough elasticity	+ Nutritional value + Texture and softness in bread and cookies	(Jiang et al. 2015; Meng et al. 2019)
Bread	• Incorporation of MBF fractions (protein/fiber) • Addition of SMBF with soy flour and mango kernel flour	• SMBF • MBF	+ H_2O absorption − Bread volume + Increased crumb firmness + Protein content Acts as a natural fat replacer	Nutrient-enriched bread with acceptable taste Potential for sustainable food production	(Indrani et al. 2015; Menon et al. 2015)
Gluten-free bread	• Use as a gluten substitute or composite flour	• SMBF • MBF	+ Protein content + Fiber content + Ash content Gluten replacement	+ Shelf-life and nutrition Good crumb structure and softness	(Sonam Gupta and Bhatt 2023; Nanyen et al. 2016)
Pasta products	• Addition to pasta dough • Extrusion • Fortification with MBF	• MBF • MBS	+ Cooking quality + Protein content + Fiber content	+ Firmness − Reduced cooking loss + Nutritional value	(Sharma et al. 2019; Singh et al. 2023)
Gluten-free pasta	• MBF used for GF formulations	• MBF	+ H_2O holding capacity Gluten replacement	+ Cooking stability Good texture and bite	(Singh et al. 2023)
Noodles	• MBS as primary ingredient • Fortification with MBP and MBF	• MBS • EMBF • GMBF	+ Chewiness + Texture retention after cooking + Antioxidant activity	+ Firmness and chewiness + Functional properties and sensory characteristics	(Diao et al. 2022; Liu et al. 2018; Ma et al. 2022; H. Zhang, Meng, et al. 2019)
Gluten-free noodles	• Use of MBS and MBF • Addition of gums to improve structure	• MBS • MBF	+ Cooking quality + Viscosity Gluten replacement	Maintained firmness and elasticity Good sensory quality with lower glycemic index	(Diao et al. 2022; Kaur et al. 2015)
Brownies	• MBF/MBP used as a wheat substitute	• MBF • MBP	+ Moisture retention + Texture + Chewiness	Denser and richer brownies + Protein and fiber content	(Rahayu et al. 2023)
Cakes	• Substitution of wheat flour with MBF	• MBF	+ Harder, gummier, and chewier texture	+ Nutritional profile + Protein content	(Ruan et al. 2019)

(Continues)

TABLE 4 | (Continued)

Product category	Processing modification	MB form used	Functional properties	Product outcomes	Citations
Gluten-free extruded products	• Incorporation of MB with rice or sorghum flour	• MBF	+ Expansion ratio + Digestibility	+ Dietary fiber + Minerals + Sensory quality	(Kaur et al. 2023; Sharma et al. 2019; Sumardiono et al. 2021)
Flat bread/chapatti	• MBF blended with cowpea and wheat flour	• MBF	+ Nutritional properties	+ Sensory scores + Desirable texture	(Balasharan and Selvi 2021)

Note: Functional properties/product outcomes (+) increased/improved and (−) decreased.
Abbreviations: EMBF = extruded mung bean flour, GF = gluten-free, GMBF = germinated mung bean flour, MBF = mung bean flour, MBP/MBPI = mung bean protein/mung bean protein isolate, MBS = mung bean starch, SMBF = sprouted mung bean flour.

enriched with bioactive properties and have been studied for their benefits to gluten-sensitive individuals or celiac patients (Taşkın and Savlak 2022). Porridge is a popular traditional dish in many Asian and sub-Saharan African countries. According to Mahgoub et al. (2020), adding soaked mung beans as an ingredient enhanced the nutritional value by increasing the availability of essential amino acids and calories in porridge. At the same time, they have incorporated mung bean into hearty stews and ground it into a flour for baking in some parts of Africa. Traditional processing techniques such as soaking, sprouting, and grinding have been employed for centuries to improve digestibility and nutrient availability. As global interest in sustainable and plant-based protein sources grows, the mung bean's ability to be transformed through these diverse processing techniques positions it as a valuable ingredient in developing novel, nutritious, and culturally diverse food products. This convergence of traditional wisdom and modern food science underscores the enduring relevance of mung bean in global cuisine and its potential to address contemporary nutritional needs.

5.2 | Utilization in Bakery and Pasta Products

5.2.1 | Bread

Mung beans, in various forms such as flour, protein isolates, or pretreated (e.g., sprouted or extruded), have shown notable improvements in the quality and nutritional value of bakery products, especially bread. For example, blending mung bean flour with wheat flour has been shown to significantly increase bread's moisture, protein, and ash content without affecting calorie or fat content. Wabi (2024) found that blending mung bean flour with wheat increased moisture, ash, and protein content, with a 50:50 blend achieving the highest protein (20.54%) without significant changes in calories or fat. Sensory evaluations showed broad acceptance, especially for the 87.5:12.5 wheat-mung bean ratio, highlighting mung bean's potential to improve bread's nutritional profile while maintaining palatability. Anosike et al. (2023) found that a 90% wheat, 5% cassava, and 5% mung bean blend-maintained bread's gluten and sensory qualities while increasing cassava and mung bean content improved fiber and protein. The study investigated the effects of replacing wheat flour with roller-milled fractions from mung bean, such as straight-run flour, protein-rich fraction, fiber-rich fraction, and a combination of protein and fiber-rich fraction, in bread preparation. It was found that while these fractions affected the volume and texture of the bread, the combination of additives improved dough strength and overall quality. The bread with 15% straight run flour, protein-rich fraction, and combination of protein and fiber-rich fraction as well as the 10% fiber-rich fraction produced acceptable quality and enhanced nutritional value (Indrani et al. 2015). Research indicates that incorporating mung bean in various forms, such as flour, protein isolates, and pretreated fractions, can significantly enhance the nutritional quality of bread without compromising sensory acceptability. In summary, mungbean flour blends with wheat flour increase protein, fiber, and moisture content while maintaining desirable texture and taste, particularly at optimized substitution levels (10%–15%).

5.2.2 | Pasta

Le et al. (2023) explored the use of mung bean by-product flour in pasta production, finding that incorporating up to 25% mung bean by-product flour increased dietary fiber and phenolic content while reducing cooking time and cohesiveness. Pasta containing 10%–20% mung bean flour showed good consumer acceptance, with the 20% level exhibiting notable antioxidant activity, highlighting mung bean by-product flour's potential in producing sustainable, high-fiber pasta. Singh et al. (2023) studied the effects of adding 10%–40% mung bean flour to barley pasta, noting improvements in water and oil absorption and increased protein, fiber, and antioxidant levels. The addition also reduced cooking time and firmness, with the 30% substitution achieving optimal sensory acceptance. FT-NIR spectroscopy analysis confirmed the presence of phenolic compounds while SEM imaging indicated a weaker pasta matrix due to the higher protein and fiber content.

Adiba et al. (2024) investigated the use of mung bean by-product flour, egg white powder, and water in gluten-free pasta, finding that mung bean by-product pasta had higher protein and fiber content than semolina pasta. In a study by Jyotsna et al. (2014), substituting split mung bean semolina at levels of 20%–80% in vermicelli resulted in increased protein and ash content, with optimal pasta quality observed at a 60% mung bean semolina level. This blend yielded 16% protein and 6% dietary fiber, with acceptable firmness and cooking characteristics. The pasta became mushy and sticky at an 80% mung bean semolina ratio, which negatively impacted its quality. Studies consistently demonstrate that mung bean and its by-products can significantly enhance the nutritional profile of pasta, increasing protein, dietary fiber, and antioxidant content.

5.2.3 | Noodles

Ma et al. (2022) investigated the γ-aminobutyric acid (GABA) content in mung beans treated with heat and relative humidity. They found that black mung beans had higher GABA levels than green varieties, and soaking increased GABA content. Heat and relative humidity treatment preserved more GABA during cooking, and noodles made from mung bean treated with heat and relative humidity showed improved color, texture, and pasting properties, highlighting the potential of GABA-rich mung bean–based foods. R. Li et al. (2023) added 15% fresh egg white to mung bean noodles, enhancing elasticity, reducing cooking loss, and improving texture and sensory qualities. Structural analysis revealed improved protein networks and starch structures, contributing to enhanced springiness and chewiness. Diao et al. (2022) investigated the hydrothermal treatment of mung bean proteins for use in wheat noodles, demonstrating that optimized heating conditions enhanced water absorption, improved texture, and reduced cooking loss. Modified mung bean proteins allowed for higher substitution levels and enhanced protein cross-linking. Liu et al. (2018) found that germinated mung bean flour improved noodle texture, reduced cooking loss, and boosted nutritional value. J. Zhou et al. (2024) found that increasing the mung bean content in buckwheat noodles improved the structure, reduced cooking loss, and increased resistant starch content. Resistant starch is known for its health benefits, including improving gut health and controlling glycemic response. Azkia et al. (2021) developed noodles from a combination of sorghum, mung bean, and sago starch, offering a balanced nutrition profile with protein, fiber, and resistant starch.

5.2.4 | Cakes

Ruan et al. (2019) explored the substitution of 50 g/100 g wheat flour with highland barley powder or mung bean flour in chiffon cakes. They observed significant changes in batter properties, such as specific gravity and viscosity. The highland barley powder cake exhibited the most uniform pore distribution, while the mung bean flour cake had a denser, chewier texture with lower specific volume, emphasizing the role of starch gelatinization and protein coagulation in cake structure. Balighi et al. (2024) investigated the impact of replacing rice flour with flours from raw and sprouted mung beans in gluten-free cakes, finding that mung bean flour improved batter consistency, cake porosity, and texture. The highest moisture content was in cakes with 20% sprouted mung bean flour. Rosfitasari and Tahir (2024) developed a nutritious steamed brownie premix with mung bean and pumpkin flours, achieving a balanced nutritional profile with optimal protein, fat, carbohydrates, and fiber.

5.2.5 | Cookies and Biscuits

Yen et al. (2023) explored gluten-free cookies by substituting rice flour with germinated mung bean flour to improve quality and nutrition. Increasing germinated mung bean flour content reduced baking loss and diameter while enhancing thickness, hardness, and vibrancy of the color. Cookies with 60% germinated mung bean flour showed similar properties to wheat flour cookies and had higher essential amino acids, offering a healthier gluten-free alternative.

Setyaningsih et al. (2019) investigated the impact of baking time on mung bean biscuits made with 60% mung bean flour, 20% wheat flour, and 20% cornstarch. Biscuits baked at 150°C for 17 min scored highest in terms of texture, color, and aroma, with a nutrient analysis revealing energy values of 445–454 kcal and a high iron content. Sustriawan (2022) developed gluten-free corn-almond cookies supplemented with mung bean flour to enhance protein content, improve moisture, and enhance texture, particularly in cookies made with virgin coconut oil. Bello et al. (2021) optimized cassava-based cookies using mung bean and coconut pomace flour, thereby enhancing their protein and caloric content.

5.3 | Extruded Products

Extrusion technology has become a cornerstone of modern food processing, particularly in the production of instant foods, ready-to-eat snacks, and alternate protein options, offering both efficiency and versatility (Kolawole et al. 2025; Pismag et al. 2023; H. Zhang, Meng, et al. 2019). It facilitates the development of food products with enhanced nutritional profiles and desirable functional properties, meeting the growing consumer

demand for convenient and nutritious alternatives. Advances in extrusion over the past decades have significantly expanded its application across various food matrices, including grain-based snacks, protein-enriched products, and gluten-free formulations. For instance, Prabha et al. (2021) highlighted how extrusion plays an essential role in the creation of instant food products, enabling rapid cooking and improving shelf life while maintaining nutritional integrity. Guo et al. (2024) further demonstrated the potential of extrusion to enhance protein cross-linking and functional properties in low-moisture products formulated with mung bean protein isolate and wheat gluten. Their study optimized the mung bean protein isolate to wheat gluten ratio to achieve superior product quality, particularly in terms of texture and rehydration kinetics.

The application of mung bean in extrusion technology has gained considerable attention, especially in gluten-free and plant-based protein formulations. Hwang et al. (2024) explored the use of isolated mung bean protein as a substitute for soy protein in high-moisture plant-based protein options, showcasing its potential to enhance fibrous structure and gelling ability. Similarly, Bozdogan et al. (2024) investigated the use of mung bean flour in extruded snacks, revealing that increasing mung bean flour content resulted in snacks with lower starch digestibility and improved physicochemical properties. De Angelis et al. (2023) provided insights into the rheological behavior of dry-fractionated mung bean protein during high-moisture extrusion cooking. Their findings demonstrated how extrusion parameters, particularly temperature and moisture content, influenced the textural properties of alternate protein options, underscoring the importance of precise control over extrusion conditions to achieve the desired product quality.

Moreover, Kaur et al. (2023) emphasized the nutritional benefits of sorghum and mung bean–based extruded snacks, which exhibited enhanced antioxidant activity and phenolic content due to the extrusion process. This highlights the potential of extrusion to improve functional properties and increase the bioavailability of health-promoting compounds. Further extending the versatility of mung bean in extrusion, Sumardiono et al. (2021) successfully produced analog rice from a blend of mung bean flour, sago, and corn flour, using hot extrusion technology. Their findings suggested that mung bean flour contributes to favorable sensory and physicochemical attributes in extruded products, reinforcing its utility in plant-based formulations.

Mung beans, in various forms, have shown significant potential in improving the nutritional quality and functional properties of a wide range of bakery, pasta, and extrusion products. Their incorporation enhances protein and fiber content and improves texture, water absorption, and cooking properties, making them a valuable ingredient in traditional and gluten-free food products. As research continues, the use of mung beans could expand further, contributing to the development of healthier, more sustainable food options.

5.4 | Nutraceuticals and Functional Foods

Mung bean has emerged as a promising source of nutraceuticals and functional foods due to its unique nutritional profile and bioactive compounds. These small, green legumes are packed with high-quality plant protein, fiber, vitamins, minerals, antioxidants, and bioactive compounds such as polyphenols, polysaccharides, and polypeptides, making them an ideal base for health-promoting products (Hou et al. 2019). Its versatility has led to the development of various innovative items, including dietary supplements. Recent research has explored the potential of fermented mung bean products, such as probiotic-rich mung bean milk and the traditional Chinese medicine preparation “Lu-doh-Huang” (Chao et al. 2013), highlighting the bean's adaptability to customary and contemporary processing methods. Research by Asrullah et al. (2016) has shown that mung bean might lower low-density lipoprotein (LDL) cholesterol levels, regulate blood pressure, improve insulin responsiveness, and support gut health through its prebiotic properties.

A comprehensive review by Tarahi et al. (2024) highlighted that the mung bean protein isolates and hydrolysates have demonstrated various health-promoting properties, including antioxidant, anti-inflammatory, cholesterol-lowering, anti-obesity, antidiabetic, antihypertensive, and anti-cancer effects. In vivo studies have shown that mung bean protein supplementation can increase the levels of antioxidant enzymes, such as superoxide dismutase and glutathione peroxidase, while reducing malondialdehyde content, indicating its potential as an antiaging agent. Yao et al. (2013) report that mung bean is a rich source of phenolic acids, demonstrating antioxidant and antidiabetic properties. Studies have underscored its health benefits, including cholesterol reduction, improved insulin sensitivity, blood pressure regulation, and gut health support. Fermented products and protein hydrolysates have shown enhanced bioactivity, with in vivo evidence suggesting antioxidant, anti-inflammatory, antidiabetic, and even antiaging potential. These findings position mung bean as a versatile candidate for developing health-promoting foods and dietary supplements.

5.5 | Innovative Applications

5.5.1 | Alternate Protein Options

The demand for plant-based protein alternatives has surged due to increasing consumer preference for plant-based products, leading to the exploration of novel ingredients like mung bean protein in the formulation of alternate protein options. Because of its favorable functional properties, mung bean protein has emerged as a promising alternative protein source. Hwang et al. (2024) found that varying isolated mung bean protein levels in high-moisture meat analogs significantly improved water binding and gelling ability, achieving optimal fibrous structures at 40%–50% isolated mung bean protein content. However, higher isolated mung bean protein concentrations negatively impacted springiness and chewiness but enhanced oil absorption capacity, which is essential for creating soft and juicy meat analogs.

In addition to the use of mung bean protein, germinated mung bean flour has also shown promise in meat-reduced sausage formulations. Le et al. (2024) demonstrated that meat blended with germinated mung bean flour at 10%–25% improved the sausage's protein, carbohydrate, and ash content, while reducing

fat and moisture. The incorporation of germinated mung bean flour also increased the total phenolic content and antioxidant capacity, making it a nutritionally superior alternative. The germinated mung bean flour substitution resulted in sausages that closely resembled the real sausages in color and texture, with enhanced emulsion stability and cooking yield, which were well accepted by consumers.

Together, these studies underscore the versatility of mung bean protein and its derivatives in developing high-quality, nutritionally enriched, and consumer-accepted plant-based meat and egg alternatives. Functional properties such as water retention, gelling ability, and emulsion stability make mung bean–based ingredients ideal for an alternative protein source in various processed food products.

5.5.2 | Packaging Films

Mung bean–based materials are emerging as promising alternatives for sustainable, biodegradable films in packaging applications. Numerous studies have investigated the potential of mung bean starch and protein to create eco-friendly substitutes for traditional plastic packaging. Roy et al. (2020) focused on developing biodegradable nano-starch–based composite films from mung bean starch. Their findings revealed that these films exhibited superior physicochemical properties compared to native starch films, including increased thickness, burst strength, reduced moisture content, and lower water vapor transmission rates. The study demonstrated that varying the nano-starch concentration between 0.5% and 10% could significantly enhance the films' suitability for packaging, underscoring their potential for eco-friendly solutions. Similarly, Su et al. (2022) created biodegradable composite plastics by combining polyvinyl alcohol (PVA), esterified mung bean starch, and gliadin. This formulation showed improved mechanical properties, biodegradability, and reduced hydrophilicity compared to pure PVA. The optimal composition (50% PVA with a mung bean starch-to-gliadin ratio of 75:25 in the PVA/starch plastic) exhibited promising properties for sustainable packaging, including enhanced tensile strength and improved water resistance.

Mojoodi and Nourani (2022) explored biodegradable films incorporating mung bean protein (1%–5%) and cumin essential oil. These films exhibited improved thickness, tensile strength, and antioxidant properties, along with reduced water vapor permeability and solubility. Although higher protein and essential oil levels increased antioxidant activity, they also decreased thermal stability. Films with 0.5 mL essential oil per gram of protein exhibited ideal mechanical and barrier properties, indicating their suitability for food packaging applications aimed at sustainable food preservation. Further advancements in mung bean–based films were made by Yao et al. (2022), who introduced citric acid as a natural cross-linker to enhance mung bean starch films' mechanical and barrier properties. Incorporating 1%–3% citric acid led to increased tensile and heat seal strength and decreased water solubility and permeability. Films with 3% citric acid concentration exhibited optimal properties, marking them as viable alternatives to plastic packaging.

In addition, Chen et al. (2023) developed a green composite film by integrating ginger essential oil. Pickering emulsions, stabilized by tempo-oxidized cellulose nanocrystals, into a mung bean starch matrix. This innovative approach significantly enhanced the film's antibacterial properties and tensile strength. Collectively, these studies demonstrate that mung bean–based materials enable biodegradable, functional films with enhanced strength, barrier, and bioactive properties, offering sustainable, safe, and versatile alternatives to conventional plastic packaging for the food industry. These innovations position mung bean–derived films as viable, eco-friendly solutions for food packaging, aligning with global sustainability goals while ensuring product safety and shelf-life extension.

5.5.3 | Beverages and Dairy Alternatives

Recent research underscores the potential of mung beans in crafting nutritious, plant-based dairy alternatives and functional beverages. Ong et al. (2024) explored mung bean for plant-based milk production. They soaked the beans in water for 12 h, blended with the addition of some more water, then filtered, and the liquid portion was cooked and cooled. This liquid was emulsified with canola oil, homogenized, and pasteurized to prepare mung bean–based milk. Mung beans showed favorable nutritional profiles and sensory qualities, along with lowered anti-nutrients and off-flavor compounds as compared to soy milk.

Joshi et al. (2023) investigated various processing methods—including soaking, blanching, and germination—to produce high-quality mung bean–based vegan milk. The germination method stood out, yielding the highest nutritional values with 4.39% protein and 5.52% carbohydrates. Combining germination with blanching enhanced the milk's viscosity, sucrose content, and total soluble solids. While all samples contained 12 amino acids, they were deficient in cystine and methionine. Notably, the germination and blanching method received the highest sensory scores, indicating its viability as a sustainable vegan milk option. Building on this, Dai et al. (2024) explored the stability of mung bean–based milk, focusing on how different raw materials affected its properties. They selected six mung bean varieties based on centrifugation sedimentation rates, discovering that stable mung bean–based milk exhibited reduced separation, smaller particle size, lower viscosity, fewer protein aggregates, and higher soluble protein content. Although the major nutritional components were consistent between stable and unstable mung bean–based milk, the stable varieties demonstrated improved protein solubility and emulsion stability, which could inform future mung bean breeding efforts.

A more general term, plant-based dairy alternatives, cover other dairy products such as fermented milk (e.g., yogurt), and cheese (Clegg et al. 2021). Yang et al. (2021) explored mung bean protein-based yogurt and observed that they produce better gel qualities, including higher hardness, chewiness, and water-holding capacity, than other protein-based (e.g., pea) yogurt, due to the presence of strong hydrophobic interactions and disulfide bonds. Additionally, they observed that specific cultures can help reduce undesirable beany flavors. On a similar line, Liang et al. (2022) observed that *L. lactis* RQ1066 fermentation in mung bean milk enhances its physicochemical properties, reduces

particle size, and improves hydrolysis, which boosts taste and sensory qualities. This process also lowers anti-nutritional factors and increases antioxidant properties, showing promise for creating nutritionally improved, plant-based functional foods. Additionally, mung bean proteins have been utilized in creating cheese analogs, such as paneer, contributing to improved nutritional profiles and unique textural properties (Tarahi 2024; Tojan et al. 2024).

In another innovative approach, Winarsi et al. (2021) developed a yogurt enriched with antioxidant phenolic compounds and soluble protein from mung beans. Their formulation, containing 85% mung bean juice and 15% skim milk, achieved the highest sensory scores among panelists, showcasing significant levels of phenolic content (525.96 mg GAE/L) and soluble protein (43.18%). This yogurt showed promise as a nutritious option.

Shamsaie et al. (2023) created a symbiotic beverage using mung bean, and rye sprouts inoculated with *Lactobacillus plantarum* and *Lactobacillus casei*, supplemented with prebiotics like inulin. The study demonstrated that both probiotics maintained good viability over a 28-day period, highlighting the beverage's potential as a nutritious option for lactose-sensitive consumers. Additionally, Kwon et al. (2021) evaluated the sensory attributes of buckwheat jelly (memilmuk) with added mung bean starch, identifying key characteristics that enhanced consumer preference. These studies collectively illustrate the versatility of mung beans in for health-conscious consumers seeking nutritious, plant-based products.

Recent advancements highlight mung bean's exceptional versatility for plant-based dairy and functional beverages, offering high nutrition, low anti-nutrients, and favorable sensory qualities. Germination, blanching, and controlled fermentation enhance protein solubility, emulsion stability, antioxidants, and probiotic viability. These findings position mung bean as a valuable ingredient in developing sustainable, nutrient-rich dairy analogs tailored for health-conscious and lactose-intolerant consumers.

6 | Future Trends and Opportunities

Mung beans are experiencing rising interest in the global food market due to shifts in consumer preferences towards plant-based proteins, sustainable food sources, and functional nutrition. With a market value expected to grow significantly in the coming years, mung beans hold promise across traditional, functional, innovative, and emerging food sectors. This allows the food industry to explore the opportunities in these areas and understand how market growth can drive mung bean applications forward.

The rising demand for ancient grains and pulses and the broader trend of incorporating them into diets for health and sustainability support mung bean demand (Akibode et al. 2012; P. K. Joshi and Rao 2016). The plant-based protein boom is projected to grow the global market revenue to USD 33.99 billion in 2027 (Andreani et al. 2023). Mung bean protein, being easy to digest, low in allergens, and sustainable, is well-positioned within this trend. Its use in high-protein snacks, meal replacements, and functional beverages will continue to expand as manufacturers seek alternatives to soy and other allergenic sources. High fiber content, antioxidant and anti-inflammatory properties, and a low glycemic index of mung beans make it a suitable ingredient for wellness foods. Mung bean–derived products, such as fortified drinks, health supplements, and snack bars, with clear benefits around inflammation and immunity, will attract health-conscious buyers.

Plant-based dairy industry shows a global retail sales value of 18 billion USD and holds around 10% of the total plant-based milk market; it is projected to grow up to 21 billion USD in 2026. The global market size for cheese alternatives was 1.01 billion USD in 2019 and projected to grow by 12.8% CAGR between 2020 and 2027 (Villarino et al. 2024). The plant-based dairy market for innovative products is expanding, with consumers showing interest in nonsoy, allergen-free, and gluten-free options. Mung beans are already used in plant-based dairy and are increasingly viewed as a viable base for dairy products like milk and yogurt due to their neutral flavor and high protein content. With continued innovation, mung beans can expand further into plant-based cheese, creamers, and other dairy alternatives. With more consumers seeking products with minimal ingredients and natural sources, mung bean–based ingredients (like flour, protein isolates, and starches) are ideal for clean-label applications. Mung bean protein and starch can improve texture and functionality in soups, sauces, and ready meals, offering simplicity in formulations and driving adoption in processed foods aimed at health-conscious consumers.

As sustainability remains a top consumer priority, the mung bean's low environmental footprint is a major asset. Requiring less water and land compared to many other protein sources, mung beans align with climate-friendly food demands, which is expected to support their market growth across plant-based sectors. With a rising focus on sustainable packaging, mung bean protein and starch show potential in creating edible films or biodegradable packaging solutions (*S.* Yao et al. 2022). Companies can leverage these for packaging snack items or creating zero-waste food wrappers, meeting the global push for eco-friendly alternatives to single-use plastic. Advances in biotechnology may result in mung bean varieties with enhanced nutritional profiles or optimized growth traits. With the plant-based market projected to continue expanding, plant breeding and biotech solutions that increase protein content or improve texture could make mung beans even more competitive against other plant-based ingredients. This would drive adoption in hybrid foods where mung bean proteins are combined with cultivated or fermentation-based proteins.

7 | Conclusions

The rapid advancements in mung bean processing and utilization underscore its immense potential as a versatile, sustainable ingredient for the future of food systems. Enhanced processing technologies, including efficient dehulling, milling, and fractionation methods, have improved mung beans' functionality, yield, and quality, making them well-suited for a wide range of

applications from bakery products to nutraceuticals. The development of advanced extrusion techniques has further expanded their use, especially in the production of plant-based protein alternatives, protein-rich snacks, and instant foods, while the isolation of high-purity mung bean proteins strengthens their role in gluten-free and high-protein formulations. The development of high-purity protein isolates and concentrates from mung beans has unlocked new opportunities for gluten-free and high-protein foods, while modifications in protein and starch content have expanded their use in nutraceuticals and functional foods. The grain's adaptability to both traditional and novel food applications demonstrates its versatility and potential to meet diverse consumer demands for clean-label, sustainable, and nutrient-rich ingredients.

Looking to the future, mung beans are positioned to capitalize on several key consumer trends, such as the shift towards plant-based, clean-label, and nutritionally enhanced foods. The continued focus on sustainability will drive further research into optimizing mung bean processing methods, with an emphasis on energy-efficient technologies and waste minimization. Additionally, protein and starch modification techniques are expected to enhance the functional properties of mung bean ingredients, expanding their applications in nutraceuticals, functional foods, and even bio-based packaging solutions.

As consumer demand for health-conscious, sustainable food options continues to rise, mung bean–based products are poised for substantial growth in traditional, innovative, and emerging food markets. These trends present an invaluable opportunity for companies and environmentally friendly products that meet the evolving needs of global consumers.

Author Contributions

Suresh Sakhare: conceptualization; investigation; resources; writing – review and editing. **Ashlyn Rairdin:** investigation; methodology; writing – original draft; writing – review and editing. **Venkata Naresh Boddepalli:** investigation; methodology; writing – original draft; writing – review and editing. **Amrita Ray:** investigation; methodology; writing – original draft; writing – review and editing. **Arti Singh:** conceptualization; supervision; project administration; writing – review and editing.

Funding

This work was supported by the R.F. Baker Center for Plant Breeding (AS), United States Department of Agriculture-National Institute of Food and Agriculture (USDA-NIFA) (Mung Bean Breeding Grant Nos. #2022-67013-37120, awarded to A.S., and #2026-67013-45812, awarded to A.S.).

Ethics Statement

This article is a review of existing literature and does not contain any original studies with human participants or animals performed by any of the authors.

Data Availability Statement

Data sharing is not applicable to this article as no new datasets were generated or analyzed during the current study. All data used in this review are available within the manuscript or through the cited references.

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