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Advancing Nutritional Quality in *Vigna mungo* (Black Gram): Integrating Agronomic, Biotechnological, and Post-Harvest Innovations

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Abstract

Vigna mungo (black gram or urad) is a nutritionally important pulse crop widely consumed for its high protein content, dietary fibre, and essential micronutrients. However, its full nutritional potential is often limited by environmental constraints, anti-nutritional factors, and suboptimal agronomic practices. Recent advances in agricultural biotechnology and food processing have opened new avenues to significantly enhance its nutritional quality. This review highlights integrated strategies involving agronomic biofortification, in vitro biotechnological interventions, and post-harvest processing techniques to improve the protein, mineral, and functional properties of *Vigna mungo*. Agronomic approaches such as targeted application of macro- and micronutrients (e.g., potassium, boron, cobalt) and stress management have shown improvements in nutrient uptake and seed quality. Biotechnological tools, including tissue culture, somaclonal variation, and nanoparticle-based elicitation, have contributed to enhanced secondary metabolite production, antioxidant activity, and genetic improvement of desirable traits. Post-harvest methods such as germination, dehulling, and microbial fermentation further improve nutrient bioavailability while reducing anti-nutritional compounds like phytic acid, oxalates, and tannins. The integration of these approaches presents a holistic pathway for developing nutritionally superior black gram varieties, contributing to food security and human health. This review emphasises a multidisciplinary framework that connects field-level cultivation practices with laboratory innovations and food processing technologies for sustainable nutritional enhancement of *Vigna mungo*.

Keywords: *Vigna mungo*, black gram, biofortification, agronomic enhancement, tissue culture, somaclonal variation, nanoparticle elicitation, germination, fermentation, nutritional quality, anti-nutritional factors, functional food

1. Selection of Superior Genetic Material in *Vigna mungo* (Black Gram)

The improvement of nutritional quality and productivity in *Vigna mungo* begins with the careful selection of superior genetic material. This step is fundamental in any breeding or biofortification program because yield, nutrient content, and stress resistance are largely governed by genotype × environment interactions. Modern breeding approaches integrate phenotypic evaluation, statistical selection tools, and disease resistance screening to identify elite germplasm suitable for further improvement.

1.1. Identification of High-Yielding and Nutrient-Rich Varieties

Selection begins with screening diverse germplasm collections and released cultivars for agronomically important traits. Key yield-contributing characters include seed yield per plant, number of pods per plant, number of clusters per plant, seeds per pod, and 100-seed weight (test weight). These traits are generally highly heritable and show strong genetic advance, making them reliable selection targets in early-generation breeding programs (Singh et al., 2013; Vavilov, 1951).

In addition to yield traits, nutritional quality traits such as seed protein content, essential amino acid profile (especially methionine and cysteine), and mineral concentration (iron, zinc, and calcium) are increasingly prioritized. Studies have shown that certain black gram genotypes exhibit significant variability in protein content ranging from 20–28%, allowing effective selection of nutrient-dense lines (Ghafoor et al., 2001).

Elite cultivars such as VBN 11, CO 6, and VBN 10 have been widely recognized for their stable yield performance, early maturity, and improved harvest index, making them suitable donor parents in breeding programs.

1.2. Germplasm Screening for Protein and Mineral Content

Systematic germplasm evaluation is essential for identifying nutritionally superior genotypes. Screening involves biochemical analysis of seeds for:

- Total seed protein (Kjeldahl method)
- Iron (Fe) and zinc (Zn) concentration (AAS or ICP-MS)
- Calcium, phosphorus, and potassium levels
- Amino acid profiling (HPLC techniques)

Genotypes exhibiting high nutrient density along with stable agronomic performance are selected as “nutritional donors” for hybridisation. Wild relatives and landraces of *Vigna mungo* are particularly valuable due to their broader genetic base and adaptive traits (Upadhyaya et al., 2011).

1.3. Selection of Stress-Tolerant Genotypes for Further Improvement

Abiotic and biotic stress resistance is a major selection criterion because yield losses in black gram due to diseases like Mungbean Yellow Mosaic Disease (MYMD) and Urdbean Leaf Crinkle Virus (ULCV) can exceed 40–50% under field conditions.

Breeding programs focus on:

- Disease resistance (MYMD, ULCV, powdery mildew)
- Pest resistance (whitefly, pod borer)
- Abiotic stress tolerance (drought, salinity, alkalinity)

Genotypes such as TU 1-30, BCU 20-62, MBG-1070, and VBG 13-003 have demonstrated resistance to major viral diseases along with high yield potential, making them valuable genetic resources for crop improvement (Nair et al., 2017).

1.4. Advanced Selection Methods Used in Breeding

Modern breeding uses statistical and biometrical tools to improve selection accuracy:

a) MGIDI Index (Multi-trait Genotype-Ideotype Distance Index)

- Identifies genotypes closest to an "ideal plant type"
- Integrates multiple traits simultaneously
- Useful for yield + nutrition + stress resistance selection

b) Mahalanobis D^2 Analysis

- Measures genetic divergence among genotypes
- Helps in selecting genetically distant parents
- Enhances heterosis in hybrid breeding

c) Pure Line Selection

- Selection of superior individual plants from landraces
- Ensures uniformity and stability in subsequent generations

These approaches significantly improve breeding efficiency and accelerate the development of improved black gram varieties (Shukla et al., 2018).

2: Agronomic Biofortification of *Vigna mungo* (Black Gram)

Agronomic biofortification is a sustainable strategy to enhance both yield and micronutrient density in *Vigna mungo* through the combined use of soil and foliar nutrient applications. It improves nutrient uptake efficiency, seed enrichment, and overall plant physiological performance. Integration of micronutrient management with macronutrient optimization, soil health improvement, and stress management forms the foundation of this approach (White & Broadley, 2009; Cakmak, 2008).

2.1. Application of Micronutrients through Soil and Foliar Sprays

Micronutrients such as Zn, B, Co, and K play essential roles in enzymatic activity, reproductive development, and grain quality enhancement.

Zinc (Zn – $ZnSO_4 \cdot 7H_2O$):

Zinc is applied through both soil and foliar methods to improve growth and nutritional quality in crops. The recommended soil application is 15–20 kg/ha as a basal dose, while foliar spraying at 0.5% concentration is effective during flowering and pod formation stages. Zinc plays a vital role in enhancing protein synthesis and significantly contributes to grain zinc enrichment, thereby improving the nutritional value of the harvested produce.

Boron (B – Borax / Disodium octaborate)

Boron is essential for reproductive development and is applied at 1.0–1.5 kg/ha through soil application. In addition, foliar sprays of 0.1–0.2% concentration are recommended at the pre-flowering stage. Boron improves pollen viability, enhances successful pod setting, and supports proper seed development, ultimately increasing yield stability and quality.

Cobalt (Co – Cobalt chloride/nitrate):

Cobalt is required in small quantities and is applied at 1.0–2.0 kg/ha through soil application. A foliar spray of 0.05% is recommended at the early vegetative stage. Cobalt plays a key role in enhancing biological nitrogen fixation by stimulating Rhizobium activity in leguminous crops, thereby improving nitrogen availability and overall plant growth.

Potassium (K – K_2SO_4):

Potassium is applied at 20–30 kg/ha as a soil application, along with foliar sprays of 1.0–2.0% concentration during the pod development stage. It improves carbohydrate transport, supports effective grain filling, and enhances plant tolerance to abiotic stresses such as drought and heat, leading to better yield and crop resilience.

2.2 Optimisation of Nitrogen and Phosphorus for Protein Synthesis

Balanced nitrogen (N) and phosphorus (P) nutrition is essential for improving seed protein content and yield in black gram.

- Nitrogen promotes amino acid and protein biosynthesis
- Phosphorus supports energy transfer (ATP) and root development

Recommended practices include:

Basal application of NPK at sowing

Split application of nitrogen for efficient uptake

Integration with *Rhizobium* inoculation to enhance biological nitrogen fixation

Adequate N and P supply has been shown to significantly increase seed protein concentration in legumes (Graham & Vance, 2003).

2.3. Improvement of Soil Health Using Organic Amendments

Soil health management is a key component of agronomic biofortification and ensures long-term productivity.

- Application of **Farmyard Manure (FYM)** improves soil organic carbon and microbial activity
- Use of **biofertilizers** (*Rhizobium*, phosphate-solubilizing bacteria, *Azotobacter*) enhances nutrient availability

Organic amendments contribute to: Improved soil structure and water-holding capacity. Enhanced nutrient mineralisation. Better root growth and nutrient uptake efficiency. Long-term studies confirm that integrated nutrient management improves both yield stability and grain nutritional quality in pulses (Subbarao et al., 2000).

2.4. Management of Abiotic Stress for Yield Stability

Abiotic stresses such as drought, salinity, and alkalinity negatively affect growth, yield, and nutrient accumulation in black gram.

Key management strategies include:

- Application of potassium and calcium to regulate osmotic balance
- Use of organic mulches to conserve soil moisture
- Selection of stress-tolerant genotypes for resilience
- Foliar application of micronutrients to reduce stress-induced damage

Zinc and potassium are particularly effective in improving drought tolerance, membrane stability, and stress resistance (Marschner, 2012).

2.5. Integrated Agronomic Biofortification Strategy (Summary)

An integrated approach ensures maximum yield and nutritional enhancement:

- Apply Zn, B, Co, and K through soil and foliar methods at critical growth stages
- Ensure balanced nitrogen and phosphorus nutrition for protein synthesis
- Improve soil fertility using FYM and biofertilizers
- Manage abiotic stress using moisture conservation and nutrient support
- Synchronise nutrient application with flowering and pod development stages for maximum grain enrichment. This integrated strategy can enhance grain yield by 10–20% and increase zinc concentration by up to 40%, making black gram both nutritionally superior and climate-resilient (Table-1).

Table-1 Recommended Agronomic Biofortification Nutrient Schedule for *Vigna mungo* (Black Gram)

Nutrient	Source Chemical	Soil Application (Basal)	Foliar Application	Critical Stage	Major Function
Zinc (Zn)	Zinc Sulphate ($ZnSO_4 \cdot 7H_2O$)	15–20 kg/ha	0.5% solution	Flowering & pod formation	Enhances protein synthesis and grain Zn enrichment
Boron (B)	Borax / Disodium octaborate	1.0–1.5 kg/ha	0.1–0.2% solution	Pre-flowering stage	Improves pollen viability, pod setting, and seed development
Cobalt (Co)	Cobalt chloride / Cobalt nitrate	1.0–2.0 kg/ha	0.05% solution	Early vegetative stage	Enhances biological nitrogen fixation via *Rhizobium* activity
Potassium (K)	Potassium sulphate (K_2SO_4)	20–30 kg/ha	1.0–2.0% solution	Pod development stage	Improves carbohydrate transport, grain filling, and stress tolerance

3: Biotechnological Enhancement

3.1 Tissue culture & micropropagation

Tissue culture and micropropagation in *Vigna mungo* (black gram) represent a highly efficient biotechnological tool for rapid multiplication of elite genotypes and conservation of superior germplasm. The technique primarily involves the use of explants such as cotyledonary nodes, shoot tips, hypocotyls, and embryonic axes cultured on Murashige and Skoog (MS) medium (Murashige & Skoog, 1962). The supplementation of cytokinins such as BAP (6-benzylaminopurine) and kinetin, along with auxins like NAA or IAA, significantly enhances direct organogenesis and shoot proliferation.

In black gram, direct regeneration systems are preferred because they minimize somaclonal variation and maintain genetic fidelity. Micropropagation not only enables year-round production of disease-free planting material but also serves as a prerequisite for genetic transformation studies, particularly Agrobacterium-mediated gene transfer. Several studies have confirmed that optimized hormone combinations significantly improve regeneration frequency and shoot elongation in legumes (George et al., 2008; Thorpe, 2007).

3.2 Somaclonal variation

Somaclonal variation refers to the genetic and epigenetic variability observed among plants regenerated through tissue culture, especially via callus-mediated indirect organogenesis (Larkin & Scowcroft, 1981). In *Vigna mungo*, this variation is considered a valuable source of novel traits, particularly for improving seed quality, yield, and stress tolerance.

Although often considered undesirable in clonal propagation, somaclonal variation provides an alternative breeding resource when conventional genetic variability is limited. Selection of beneficial variants with improved biochemical composition, disease resistance, or drought tolerance has been widely reported in leguminous crops (Evans et al., 1984; Kaeppler et al., 2000). Screening regenerated plantlets under controlled conditions allows identification of stable variants that can be advanced into breeding programs.

3.3 Nanoparticle elicitation

Nanoparticle-based elicitation is an emerging field in plant biotechnology where engineered nanoparticles such as ZnO, CuO, Ag, and FeO are used to stimulate plant metabolic activity in vitro. In *Vigna mungo*, nanoparticle exposure has been shown to enhance phenolic content, antioxidant activity, and stress-responsive enzyme systems.

ZnO and CuO nanoparticles act as abiotic elicitors by inducing reactive oxygen species (ROS) signaling at low concentrations, thereby activating secondary metabolite biosynthesis pathways. This results in enhanced accumulation of flavonoids, phenolics, and other antioxidant compounds, which improve plant defense and physiological performance (Rai et al., 2012; Mittler, 2017). However, concentration-dependent toxicity must be carefully optimized to avoid growth inhibition.

3.4 In vitro selection

In vitro selection is a powerful biotechnological approach used to identify stress-tolerant and nutritionally superior genotypes at the cellular or tissue level. In this technique, cultured explants or calli are exposed to selective pressures such as salinity (NaCl), drought mimetics (PEG), heavy metals, or nutrient stress. Only tolerant cell lines survive and regenerate into whole plants.

In *Vigna mungo*, in vitro selection has been effectively used to develop salt-tolerant and drought-resilient lines with improved physiological efficiency and nutrient uptake. This method significantly reduces the time required for conventional breeding and enhances precision in selecting desirable traits (Zhang et al., 2001; Jain, 2001). The selected lines often show improved photosynthetic efficiency, osmotic adjustment, and higher yield stability under field stress conditions.

4: Controlled Cultivation and Crop Management

4.1 Maintain optimised irrigation and nutrient schedules

Efficient irrigation and nutrient management are fundamental to achieving high productivity and quality in *Vigna mungo* (black gram). The crop performs well in tropical and subtropical climates with temperatures ranging from **25–35°C** and grows best in well-drained loam to clay loam soils with a pH of **6.0–7.0**. A balanced nutrient schedule consisting of **15 kg N, 40 kg P_2O_5, 20 kg S ha^{-1}**, along with **20 t ha^{-1} of farmyard manure (FYM)**, provides an adequate nutrient supply for optimum plant growth (ICAR-IIPR, 2023). Seed inoculation with **Rhizobium** and **Phosphobacteria** cultures before sowing enhances biological nitrogen fixation and phosphorus availability, thereby improving nutrient-use efficiency and reducing dependence on chemical fertilizers (Graham & Vance, 2003). During the kharif season, black gram is generally cultivated under rainfed conditions, requiring only one life-saving irrigation during the early pod formation stage, whereas summer crops require **3–4 irrigations** depending on soil moisture conditions. Waterlogging should be strictly avoided because it impairs root development, nodulation, nutrient absorption, and ultimately grain yield (Singh et al., 2017).

4.2 Ensure pest and disease management using eco-friendly approaches

Integrated pest and disease management (IPDM) is essential for sustainable black gram cultivation. Weed competition can be minimized through **two hand weedings at 15 and 30 days after sowing (DAS)** or by the application of the pre-emergence herbicide **pendimethalin**, ensuring better crop establishment and nutrient utilization (ICAR-IIPR, 2023). Major insect pests, including aphids (*Aphis craccivora*), whiteflies (*Bemisia tabaci*), and pod borers (*Helicoverpa armigera*), significantly reduce yield if left unmanaged. Eco-friendly approaches such as neem-based botanical formulations (e.g., **Achook** and **Nimbecidin**) applied at **3–5 ml L^{-1}** effectively suppress pest populations while preserving beneficial insects and reducing pesticide residues (Isman, 2006). Furthermore, biological control agents, crop rotation, resistant varieties, field sanitation, and regular pest surveillance are integral components of integrated pest management (IPM), reducing dependence on synthetic pesticides and promoting environmental sustainability (Koul & Walia, 2009).

4.3 Apply growth regulators to improve flowering and pod formation

The exogenous application of plant growth regulators (PGRs) significantly enhances flowering, pod set, seed filling, and yield in *Vigna mungo*. Foliar application of **naphthalene acetic acid (NAA; 20–40 ppm)**, **gibberellic acid (GA_3; 20–50 ppm)**, **salicylic acid (100–200 ppm)**, and **brassinosteroids** during the pre-flowering and flowering stages improves pollen viability, flower retention, pod formation, and grain filling (Taiz et al., 2018). In addition, exogenous polyamines such as **putrescine (1.5 mM)** and **cadaverine (1.0 mM)** stimulate protein synthesis, antioxidant enzyme activity, and stress-responsive metabolic pathways, resulting in a significant increase in biological yield and seed protein content (Kumar et al., 2021). Seaweed liquid fertilizers (SLFs), particularly those derived from *Sargassum* species, contain natural phytohormones including auxins, cytokinins, and gibberellins that improve chlorophyll content, relative leaf water content, salt tolerance, flowering efficiency, and pod development, thereby contributing to enhanced crop productivity under both normal and stress conditions (Craigie, 2011; Sharma et al., 2014).

5: Harvest at physiological maturity for maximum nutrient retention

Harvesting *Vigna mungo* (black gram) at physiological maturity is essential for maximizing grain quality, nutritional value, and marketability. The crop generally reaches maturity within **75–130 days**, depending on the cultivar and growing season. Harvesting should be carried out when approximately **70–80% of the pods have turned dark brown or black**, indicating physiological maturity and maximum accumulation of proteins, carbohydrates, and minerals (ICAR-IIPR, 2023). Delayed harvesting increases the risk of pod shattering, seed deterioration, and field losses, whereas premature harvesting results in immature seeds with lower nutritional quality and poor germination. Manual harvesting by uprooting the entire plant or cutting it close to the ground with a sharp sickle is recommended to minimize mechanical damage. Harvesting should preferably be performed during dry weather to avoid moisture absorption and fungal contamination. After harvesting, plants should be stacked uniformly on a clean threshing floor for **7–10 days** to facilitate uniform sun drying before threshing. Proper threshing and winnowing on clean concrete or tarpaulin surfaces reduce grain contamination and mechanical injury, thereby preserving seed quality and nutrient composition (Singh et al., 2017; FAO, 2019).

5.1 Proper drying and storage to prevent nutrient degradation

Post-harvest drying and storage are critical for maintaining the nutritional and physiological quality of black gram seeds. After threshing and winnowing, seeds should be sun-dried for **3–4 days** on clean plastic sheets, tarpaulins, or concrete floors until the moisture content is reduced to **8–10%**, which is considered safe for long-term storage (FAO, 2019). Drying to the recommended moisture level minimizes respiration, enzymatic activity, fungal growth, and insect infestation, thereby preventing deterioration of proteins, vitamins, and other essential nutrients. Before storage, grains should be thoroughly cleaned and graded to remove broken, shriveled, and infected seeds. Storage in **airtight containers, Purdue Improved Crop Storage (PICS) bags, treated jute bags, or moisture-proof bins** within clean, dry, well-ventilated, and rodent-proof facilities effectively protects the grain from moisture uptake and pest attack. Where necessary, approved grain protectants or fumigants should be applied according to recommended safety guidelines.

Proper post-harvest handling significantly reduces storage losses, maintains seed viability and nutritional quality, and enhances the market value of black gram (Golob et al., 2002; ICAR-IIPR, 2023).

6: Processing Techniques for Nutritional Enhancement

6.1 Soaking

Soaking is one of the simplest and most effective pre-processing techniques for improving the nutritional quality of *Vigna mungo* (black gram). Seeds are typically soaked in clean water for **12–24 hours** before cooking or further processing. This process initiates metabolic activity, softens the seed coat, and facilitates the leaching of water-soluble anti-nutritional compounds such as phytates, tannins, and oxalates. Soaking also shortens cooking time, improves starch digestibility, and enhances the bioavailability of essential minerals including iron, zinc, and calcium. When followed by pressure cooking, soaking can reduce **phytates by approximately 61%**, **oxalates by nearly 60%**, and completely eliminate heat-labile trypsin inhibitors, thereby improving protein digestibility and overall nutrient utilization (Shimelis & Rakshit, 2007; Khattab & Arntfield, 2009).

6.2 Dehulling

Dehulling involves the removal of the seed coat to produce split black gram (dal), resulting in improved palatability, faster cooking, and enhanced digestibility. Since the majority of anti-nutritional compounds are concentrated in the outer seed coat, dehulling substantially reduces their concentration. Studies have reported reductions of **72.03% in polyphenols, 69.23% in phytates, 60.54% in tannins, and 46.59% in oxalates** following soaking and dehulling. Although slight reductions in dietary fiber and certain micronutrients may occur, dehulling markedly increases protein digestibility and mineral bioavailability, making black gram more suitable for human consumption, particularly for children and elderly individuals (Reddy et al., 1985; Shimelis & Rakshit, 2007).

6.3 Germination (Sprouting)

Germination is an effective biological process that significantly enhances the nutritional and functional properties of black gram. Seeds are soaked for **12–24 hours** and allowed to germinate for **48–72 hours** under controlled moisture and temperature conditions. During germination, endogenous enzymes such as phytase, protease, and amylase become activated, leading to the hydrolysis of storage compounds and anti-nutritional factors. Consequently, crude protein content may increase to **approximately 28%**, while vitamin C, free amino acids, and antioxidant compounds also increase substantially. Germination significantly reduces phytic acid and tannin concentrations, thereby enhancing the absorption of minerals such as iron, zinc, and calcium. Furthermore, sprouting improves protein digestibility, starch utilization, and antioxidant capacity, making germinated black gram an excellent functional food ingredient (Frias et al., 2005; Ghavidel & Prakash, 2007).

6.4 Fermentation

Fermentation is a traditional bioprocessing technique that further enhances the nutritional value of *Vigna mungo*. During fermentation, soaked seeds or flour are inoculated with beneficial microorganisms such as **Lactobacillus spp.** and **Saccharomyces spp.**, which produce hydrolytic enzymes that degrade anti-nutritional compounds. Fermentation improves protein digestibility by breaking down complex proteins into readily absorbable amino acids and peptides. It also increases the synthesis of B-complex vitamins, enhances antioxidant activity, and improves mineral bioavailability through phytate degradation. Additionally, fermentation develops desirable flavor, texture, and shelf stability while increasing the functional properties of black gram-based foods such as idli, dosa, and fermented pulse products (Steinkraus, 1996; Marco et al., 2017).

7: Development of Protein-Rich Flours and Health Supplements

Vigna mungo (black gram) is an excellent source of plant-based protein, dietary fiber, essential amino acids, minerals, and bioactive phytochemicals, making it an ideal raw material for the development of protein-rich flours and nutraceutical health supplements. Black gram flour and protein isolates possess desirable techno-functional properties, including high water absorption, emulsification, foaming, gelation, and binding capacities, which enhance their suitability for functional food formulations. Processing techniques such as germination, fermentation, and dehulling further improve protein digestibility, amino acid availability, antioxidant activity, and mineral bioavailability by reducing anti-nutritional factors such as phytates, tannins, and trypsin inhibitors. Germinated black gram flour contains increased levels of bioactive peptides, vitamins, and antioxidants, making it highly suitable for the preparation of protein powders, nutritional beverages, sports nutrition products, meal replacement supplements, and therapeutic foods for individuals with protein-energy malnutrition, diabetes, and cardiovascular disorders (Ghavidel & Prakash, 2007; Khattab & Arntfield, 2009; Day, 2013).

7.1 Use in Fortified Food Formulations (Baby Food, Protein Blends)

The nutritional and functional characteristics of black gram make it an important ingredient in fortified food formulations designed for infants, children, pregnant women, elderly individuals, and other nutritionally vulnerable populations. Dehulled and germinated black gram flour is widely incorporated into complementary baby foods, weaning mixes, protein-enriched porridges, composite flours, biscuits, cookies, noodles, pasta, and ready-to-eat snacks because of its high protein content, balanced amino acid profile, and improved digestibility. Incorporation of approximately **10–20% black gram flour** into cereal-based formulations significantly enhances protein quality, dietary fiber, iron, calcium, and zinc contents while improving dough characteristics through increased water absorption and emulsification properties. In addition, fermented black gram products synthesized using lactic acid bacteria exhibit improved B-complex vitamin content, enhanced antioxidant activity, and greater mineral bioavailability, making them highly suitable for functional and therapeutic foods. Owing to its naturally low glycemic index and enzyme inhibitory properties, black gram is increasingly utilized in diabetic foods, gluten-free formulations, high-protein blends, and plant-based dairy and meat alternatives (Sharma et al., 2014; Marco et al., 2017; Boye et al., 2010).

7.2 Industrial-Scale Processing for Nutraceutical Applications

Industrial processing of *Vigna mungo* has expanded considerably due to growing consumer demand for plant-based functional foods and nutraceutical ingredients. Modern processing technologies, including dry and wet milling, protein isolation, membrane filtration, extrusion cooking, spray drying, freeze drying, germination, and solid-state fermentation, are employed to produce high-value functional ingredients with superior nutritional and techno-functional properties. Protein concentrates and isolates derived from black gram are extensively used in protein supplements, fortified beverages, nutrition bars, meat analogues, dairy substitutes, and medical nutrition products because of their excellent emulsifying, foaming, and gel-forming characteristics. Furthermore, black gram contains abundant flavonoids, polyphenols, dietary fiber, and antioxidant compounds that exhibit antidiabetic, antihyperlipidemic, anti-inflammatory, antimicrobial, and cardioprotective activities, making it a valuable source of nutraceutical ingredients. Industrial-scale fermentation with Generally Recognized As Safe (GRAS) microorganisms further enhances protein digestibility, antioxidant capacity, and the production of bioactive peptides, supporting the commercialization of black gram-based functional foods, dietary supplements, and pharmaceutical formulations aimed at preventing lifestyle-related disorders (Day, 2013; Granato et al., 2020; Shahidi, 2009).

8: Integration into Sustainable Agriculture and Future Prospects

8.1 Integration into Sustainable Agriculture

Vigna mungo (black gram) plays a pivotal role in sustainable agricultural systems because of its ability to improve soil fertility, enhance cropping system productivity, and reduce dependence on synthetic fertilizers. As a leguminous crop, black gram establishes a symbiotic association with **Rhizobium** bacteria, enabling biological nitrogen fixation of approximately **30–50 kg N ha^{-1}**, thereby enriching soil nitrogen and reducing fertilizer requirements for subsequent cereal crops such as rice and wheat (Graham & Vance, 2003). Consequently, black gram is widely incorporated into crop rotation systems to improve soil structure, organic carbon content, microbial activity, and nutrient cycling.

Intercropping black gram with cereals such as sorghum, maize, pearl millet, and finger millet, as well as commercial crops including cotton and sugarcane, improves land-use efficiency, resource utilization, and overall system productivity. Such cropping systems have been reported to increase total productivity by **42–53%**, while simultaneously suppressing weed populations by **20–45%** through better canopy coverage and competition (Willey, 1979; Lithourgidis et al., 2011). In addition, integrated nutrient management (INM), which combines **50–100% of the recommended fertilizer dose (RDF)** with farmyard manure (FYM), vermicompost, green manures, and biofertilizers such as **Rhizobium** and **Phosphate Solubilizing Bacteria (PSB)**, significantly improves plant growth, nodulation, nutrient-use efficiency, grain yield, and long-term soil fertility while reducing environmental pollution (Mahajan et al., 2012; ICAR-IIPR, 2023). These sustainable practices contribute to improved soil health, enhanced biodiversity, reduced greenhouse gas emissions, and resilient farming systems.

8.2 Future Prospects

Despite its nutritional and agronomic importance, *Vigna mungo* production continues to face significant challenges due to abiotic stresses, biotic constraints, and a relatively narrow genetic base. Heat stress during flowering and pod development can reduce seed yield by **38–82%**, while drought, salinity, and irregular rainfall associated with climate change further limit productivity (Nair et al., 2019). Major diseases such as **mungbean yellow mosaic disease (MYMD)** and **urdbean leaf crinkle virus (ULCV)**, together with insect pests including whiteflies (*Bemisia tabaci*), aphids, and pod borers, remain major constraints to sustainable production (Basak et al., 2004). Moreover, limited genetic diversity among cultivated varieties restricts the development of high-yielding, stress-resilient cultivars through conventional breeding.

Future research is increasingly focused on the development of **climate-smart black gram cultivars** that combine high yield potential with tolerance to drought, heat, salinity, and emerging pests and diseases. Modern breeding approaches integrating **marker-assisted selection (MAS), quantitative trait loci (QTL) mapping, genomic selection, genome sequencing, and introgression of genes from wild *Vigna* relatives** are accelerating the development of resistant and nutrient-rich cultivars (Varshney et al., 2019). Biotechnological interventions, including tissue culture, genetic transformation, CRISPR/Cas-based genome editing, and speed breeding, offer promising opportunities for rapid crop improvement. In addition, black gram is gaining increasing importance in the functional food and nutraceutical industries owing to its high-quality proteins, dietary fiber, resistant starch, flavonoids, polyphenols, and antioxidant compounds that contribute to the prevention and management of diabetes, cardiovascular diseases, obesity, and metabolic disorders (Boye et al., 2010). Strengthening decentralized quality seed production systems, digital agriculture, precision nutrient management, climate-resilient agronomic practices, and effective extension services through front-line demonstrations will facilitate the adoption of improved cultivars among smallholder farmers. Collectively, these advances position *Vigna mungo* as a strategic crop for achieving sustainable agriculture, nutritional security, climate resilience, and food system sustainability in the coming decades.

Conclusion

Nutritional enhancement of *Vigna mungo* (black gram) is essential for improving food and nutritional security, particularly in regions where pulses serve as a major source of plant-based protein and micronutrients. Agronomic biofortification provides a practical and sustainable approach to increasing grain yield and improving the concentration of essential minerals such as zinc, boron, cobalt, and potassium through integrated soil and foliar nutrient management. Simultaneously, balanced nitrogen and phosphorus nutrition enhances protein synthesis, while the incorporation of organic amendments and biofertilizers improves soil fertility, nutrient availability, and long-term agricultural sustainability.

The integration of modern biotechnological tools, including germplasm screening, tissue culture, somaclonal variation, and nanoparticle-assisted elicitation, offers additional opportunities for developing nutrient-rich and stress-tolerant black gram cultivars. Furthermore, post-harvest processing techniques such as germination, dehulling, and fermentation significantly improve nutrient bioavailability and reduce anti-nutritional compounds, thereby increasing the nutritional and functional value of black gram for human consumption.

Future research should focus on combining agronomic biofortification with molecular breeding, genomics-assisted selection, genome editing, and precision agriculture to accelerate the development of climate-resilient, high-yielding, and nutrient-dense black gram varieties. Integrating these multidisciplinary approaches with farmer-friendly cultivation practices and supportive agricultural policies will strengthen sustainable pulse production, improve public health, and contribute to the achievement of global food security and sustainable development goals.

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