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UNDERUTILIZED PULSES: A REVIEW ON NUTRITIONAL PROFILES, GENETIC RESOURCES AND FUTURE OUTLOOK

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ABSTRACT
Global food security and nutritional resilience are increasingly threatened by over-reliance on a narrow basket of major staple crops. Minor pulses including rice bean (*Vigna umbellata*), horse gram (*Macrotyloma uniflorum*), moth bean (*Vigna aconitifolia*), adzuki bean (*Vigna angularis*), represent an underutilized repository of climate-smart agriculture with rich sources of macro and micronutrients. This review compiles the nutritional compositions of these orphan crops, emphasizing their competitive protein, mineral, and resistant starch contents relative to widely cultivated commercial legumes. We detail their multifaceted therapeutic benefits, ranging from glycaemic regulation to anti-urolithiasis and cardiovascular protective pathways. Crucially, this paper establishes a novel operational bridge between available genetic resources and contemporary breeding strategies. We dissect the deployment of molecular breeding, high-throughput phenotyping, genomic-assisted selection, multi-parent advanced generation intercross (MAGIC) populations, and targeted CRISPR/Cas9 genome editing aimed at correcting agronomic defects (e.g., indeterminate growth, pod shattering) and eliminating key anti-nutritional factors (e.g.,trypsin inhibitors, phytic acid). Finally, we outline an integrated multi-omics roadmap and value-chain intervention strategy designed to transition minor pulses into mainstream global functional food networks.

KEYWORDS: breeding strategies, genetic resources; minor pulses; nutritional profile

1. INTRODUCTION
Modern agricultural paradigms suffer from dangerous homogenization. Out of thousands of edible plant species, less than ten crops fulfil the vast majority of global caloric requirements. This systemic lack of diversification has triggered severe environmental vulnerabilities and escalated a global public health crisis known as "hidden hunger," or chronic micronutrient malnutrition. Among legumes, major commercial crops such as chickpea (*Cicer arietinum*), pigeon pea (*Cajanus cajan*), and soybean (*Glycine max*) dominate research funding and international markets. Conversely, minor pulses remain geographically localized, largely managed by smallholder subsistence farms in arid and semi-arid regions of Asia and Africa. Minor pulses such as Horse Gram, Moth Bean, Rice Bean, Adzuki Bean, are nutrient dense, climate-resilient crops. These versatile legumes provide essential nutrition under challenging environmental conditions, including arid and acidic soil environments.
Despite their current status as "orphan crops," minor pulses possess extraordinary physiological plasticity. They fix atmospheric nitrogen efficiently, thrive on marginal soils with minimal chemical input, and display intrinsic resistance to extreme temperatures and moisture deficits. More importantly, their nutritional profiles include substantial amounts of protein, minerals, dietary fibre, and other bioactive compounds. Resolving the dual challenges of climate adaptation and nutritional insecurity demands a comprehensive reappraisal of these resilient crops.
The focus of this review centres on four key minor pulses: rice bean (*Vigna umbellata*), horse gram (Macrotyloma uniflorum), moth bean (*Vigna aconitifolia*), adzuki bean (*Vigna angularis*). Until recently, these grains were constrained by wild genetic traits like indeterminate flowering and low mineral bioavailability caused by anti-nutritional factors (ANFs). However, modern breakthroughs in high-throughput sequencing, multi-omics integration, and CRISPR/Cas9 genome editing are shifting the paradigm. This review provides an in-depth synthesis of their biochemistry, pharmaceutical potential, germplasm diversity, modern genetic breeding blueprints, and future commercial value chains.

REVIEW METHODOLOGY
A comprehensive literature search was conducted across electronic databases including Google Scholar, PubMed, Scopus, etc., using various search strings related to minor pulses such as minor pulses, orphan legumes, rice bean, horse gram, moth bean and adzuki bean, with target themes like nutritional profiling, bioactive compounds, genomics, and crop

improvement. The literature comprised peer-reviewed original research, and critical reviews focusing on the nutritional, therapeutic, or genetic aspects of underutilized pulses. Data from the selected literature were extracted and categorized into five distinct thematic matrices: 1. macro- and micronutrient composition, 2. therapeutic evidence, 3. germplasm diversity and genebank resources, 4. conventional and molecular breeding advancements and 5. socio-economic and climate-resilient future trajectories.

1. Key Minor Pulses: Profiles and Therapeutic Benefits

1.1. Rice Bean (*Vigna umbellata*)

Rice bean is a multipurpose, vigorous legume grown primarily in humid subtropical regions of Asia. Unlike most other minor pulses, it exhibits excellent tolerance to waterlogging, highly acidic soils, and heavy aluminium toxicity (1). It accumulates exceptionally high concentrations of calcium (up to 450 mg/100g), making it a natural dietary defence against osteoporosis and bone density loss supporting bone health (2). It is rich in both iron and folic acid (B9), it serves as an excellent natural biofortification food to combat iron-deficiency anaemia (1).

1.2. Horse Gram (*Macrotyloma uniflorum*)

Horse gram is a highly climate-resilient, viny legume native to the Indian subcontinent. It is renowned for its extreme drought tolerance and ability to thrive on poor, marginal soils where other crops fail, often serving as a reliable emergency crop (3,4). It is investigated for its anti-urolithiasis properties, which may support the prevention and management of calcium oxalate kidney stones (4,5,6). It has a very good weight and diabetes management, which is packed with raw iron and high-density dietary fibre, it significantly reduces postprandial blood glucose spikes and aids in fat metabolism (4,5,7).

1.3. Moth Bean (*Vigna aconitifolia*)

Moth bean is an exceptionally drought-resistant legume native to arid regions of South Asia. It features a low growing, mat-forming growth habit that acts as an excellent soil binder, reducing moisture evaporation and combating wind erosion in desert margins (8). It supports gut health and immunity as it has a high concentration of zinc and magnesium, which helps boost cellular immunity and supports gut lining repair (9,10). The seed contains bioactive peptides and plant sterols, which are associated with maintaining healthy LDL cholesterol levels and supporting a balanced inflammatory response. (8,9,11).

1.4. Adzuki Bean (*Vigna angularis*)

Adzuki Bean is widely cultivated across East Asia, the adzuki bean is a bush-type or semi-twining pulse. It produces striking red seeds and is highly valued for its sweet flavour and steady, uniform growth patterns under cooler agricultural climates (12). It is rich in soluble dietary fibre and polyphenolic compounds, it may support glycaemic regulation by interacting with alpha-glucosidase enzymes, making it a useful dietary component for managing blood sugar levels (13). It provides molybdenum, a trace mineral that supports normal, enzyme-dependent metabolic pathways within the liver and renal systems (12,14).

2. Nutritional Architecture and Composition

Minor pulses have diverse biochemical profiles containing important macronutrients, minerals, dietary fibre, and other bioactive compounds. Their crude protein content generally ranges from 18% to 29.5% of dry seed weight, indicating that these crops can provide substantial amounts of dietary protein.

From a qualitative standpoint, minor pulses possess excellent amino acid profiles. Unlike most cereal grains, which are intrinsically deficient in lysine, species such as *Vigna umbellata* (rice bean) and *Vigna angularis* (adzuki bean) are rich in lysine (exceeding 6.5 g/16 g N in some adzuki cultivars) (15). While sulphur containing amino acids (methionine and cysteine) remain the primary limiting factors, a trait common across the Fabaceae family the overall Protein Digestibility Corrected Amino Acid Score (PDCAAS) of minor pulses indicates high nutritional efficiency when paired with a traditional cereal matrix, since the amino acid profiles mutually complement each other to form a complete protein source (16,17).

The lipid content of minor pulses is generally low, although the fatty-acid composition varies among species and genotypes, with unsaturated fatty acids constituting an important proportion of the lipid fraction (18). The key nutritional characteristics of selected underutilized pulses are summarized in Table 1.

Table 1. Nutritional Composition in Minor Pulses

Component	Rice bean	Horse gram	Moth bean	Adzuki bean	References
PROXIMATE COMPOSITION (%)					
Moisture	11.0-13.8	10.2-12.5	10.0-11.8	10.0-12	(19,20,21)
Carbohydrates	60.7-65.5	55.6-63.8	60.0-62.0	57.0-62.0	
Protein	17.8-25.1	18.5-29.5	21.0-24.0	18.8-24.5	
Fat	0.6-1.2	0.4-1.1	1.5-2.2	0.3-1.3	
Fibre	4.0-5.8	5.3-7.2	6.5-8.0	4.5-7.5	
Ash	3.81-4.06	2.8-4.2	2.5-3.6	3.0-4.2	
MINERALS (mg 100 g^{-1})					
Calcium	315–450	240–287	150–160	75-253	

Phosphorus	301–480	310–345	200–240	213-333	(19,20)
Iron	7.2–10.9	6.2–9.8	6.0–7.5	5.4-7.6	
Magnesium	180–210	180–210	130–150	120-236	
Zinc	2.1–3.4	2.1–3.4	1.6–2.5	2.4-3.9	
VITAMINS					
Thiamine (mg)	0.39–0.57	0.35-0.47	0.30–0.45	0.45-0.50	(19,20)
Niacin (mg)	2.2–2.4	1.8–2.2	1.6–2.1	2.2-2.6	
Vitamin A IU	30	20	15	15-20	
ESSENTIAL AMINO ACIDS (g 100 g^{-1} protein)					
Lysine	5.60–7.73	5.42-7.17	5.10–6.77	6.40-7.80	
Leucine	6.17–9.50	6.60-8.70	6.12– 8.38	7.10-8.25	
Isoleucine	2.10– 5.78	2.01-5.15	1.90– 4.90	3.80-4.60	(19)
Methionine	0.45– 1.18	0.35-1.08	0.35– 0.92	0.85-1.15	
Threonine	3.12– 4.57	2.94-4.35	2.70– 4.10	3.20-3.95	
Valine	3.27– 5.23	3.25-5.02	2.90– 4.65	4.30-5.20	

2.1 Anti-Nutritional Compounds

Anti-nutritional factors such as phytic acid, tannins, saponins, lectins, protease inhibitors, and amylase inhibitors are commonly present in minor pulses and can interfere with protein digestion and reduce the bioavailability of essential minerals, particularly iron and zinc (22). The major anti-nutritional factors reported in minor pulses are summarized in Table 2. If consumed without proper processing, elevated levels of these compounds may lead to micronutrient deficiencies in populations that depend heavily on plant-based foods. However, various traditional and modern processing methods including soaking, germination, fermentation, roasting, and thermal treatments are effective in reducing these anti-nutritional factors and enhancing nutrient availability. The elimination of these factors improves digestibility, nutritional quality, and the overall utilization of minor pulses in human diets.

Table 2. Major Anti-nutritional Compounds Reported in Minor Pulses

Crop	Phytic acid (mg/g)	Tannins (mg/g)	Trypsin inhibitor (TIU/100g)	References
Rice bean	20.50	14.4	3500	(20)
Horse gram	12.03	9.03	925	(20,23)
Moth bean	4.20	6.5-28.9	12,210-13,560	(24,25)
Adzuki bean	0.07	0.6-1.1	35.23	(20)

3. Crop Wild Relatives (CWRs) and Landraces of Minor Pulses

3.1. Horse Gram (*Macrotyloma uniflorum*)

The geographical centre of diversity for horse gram with primary gene rich centres are the span tropical Southern Asia (particularly India) and parts of Central, East, and Southern Africa (26). Macrotyloma uniflorum var. stenocarpum is the key species and the primary wild botanical variant native to dry woodland savannahs and regions spanning Central to Eastern Africa. The wild Macrotyloma species found across dry, deciduous African woodlands (27). Highly adaptive seed morphology suited for extreme drought, deep-root systems, and high total soluble solids or rustic survival mechanisms against poor soil moisture (3,28). Indian landraces (such as those from the foothills of Himachal Pradesh, Uttarakhand, and Jammu & Kashmir) maintain distinct seed sizes and variations in therapeutic Ayurvedic properties (3,29).

3.2. Moth Bean (*Vigna aconitifolia*)

The geographical Centre of Diversity for moth bean is exclusively the Indian subcontinent origins, predominantly the rainfed ecosystems of Rajasthan and Gujarat (21,30). Vigna trilobata (closely linked in the aconitifolia - trilobata complex, exhibiting higher wild diversity) (30) is the key crop wild relative with unique among the Asiatic Vigna, the cultivated moth bean has retained its wild-type morphology to a high degree. Its wild relatives possess valuable traits evolutionary adaptations for high evaporative stress, heavy pod-bearing clusters per plant, and exceptional tolerance to scarce desert rainfall (21). Landraces like Madaki or Tulkapayir that feature highly trailing, twining architectures optimized for mixed cropping and soil-moisture preservation in scrub jungles (30,31).

3.3. Rice Bean (*Vigna umbellata*)

The geographical centres of diversity for rice bean encompass the Indo-China region, expanding extensively across Southern China, Nepal, India, and Bangladesh (30) are the geographical centers of diversity for Rice bean. The key wild relatives are *Vigna dalzelliana* (highly similar genetically with umbellata) and *Vigna minima* (from the angularis-umbellata / adzuki bean group) (30). Wild varieties show the absolute highest level of sequence variation (via SSR and

SNP markers) compared to narrow domesticated lines. They harbor genes regulating short flowering times across diverse latitudes and natural protection against common storage pests and fungal diseases (2). Landraces such as FF25 with mapped reference genomes contain copy number variations (e.g., VumCYP78A6) and can be exploited to boost seed yield under extreme climatic shifts (32).

3.4. Adzuki Bean (*Vigna angularis*)

The primary origin and centre of diversity for Adzuki Bean is East Asia (China), with subsequent independent regional selection and diversification pathways across Japan and the Korean Peninsula (12). The key crop wild relatives are *Vigna angularis var. nipponensis*, the wild ancestral progenitor broadly distributed across temperate East Asian woodlands and riverbanks (33). Valuable traits with inherent genetic adaptation to harsh environments, providing critical reservoirs for drought avoidance, salinity tolerance, and specialized waterlogging resistance (33). Landrace reservoirs are maintained across extensive East Asian germplasm networks, preserving distinct subpopulation structures, diverse seed coat colorations, and wide environmental adaptability (34,35). The reported nutritional traits of crop wild relatives (CWRs) associated with minor pulses are presented in Table 3.

Table 3. Crop Wild Relatives of minor pulses reported for various nutritional traits

Crop	Crop Wild relative (s)	Reported nutritional traits	References
Rice bean	*V. dalzelliana, V. minima* and wild accessions	Substantial levels of protein, iron, zinc, dietary fibre, phenolics and stress-related metabolites	(1,21)
Horse gram	*Macrotyloma uniflorum* var. stenocarpum and other Macrotyloma spp.	Notable levels of protein, iron, calcium, flavonoids, phenolics and antioxidant activity; also higher tannins and trypsin inhibitors	(20,21)
Moth bean	*Vigna trilobata, V. stipulacea, V. sublobata*	Enriched in seed protein, iron, calcium, polyphenols, antioxidant activity, α-amylase inhibitors and bruchid resistant proteins	(21)
Adzuki bean	*Vigna angularis var. nipponensis*	Greater anthocyanin accumulation, phenolics, flavonoids, antioxidant activity and dietary fibre	(20,23)

4. Genetic Resources, Crop Diversity and Germplasm Repositories

Developing minor pulses into elite, stable crops depends on effectively utilizing their diverse wild gene pools. Thousands of accessions representing minor legumes are secured across international gene banks, notably the National Bureau of Plant Genetic Resources (ICAR-NBPGR, India), the World Vegetable Centre (WorldVeg/AVRDC, Taiwan), and the International Centre for Agricultural Research in the Dry Areas (ICARDA) (21,36). However, a large portion of these stored accessions remains under-characterized (21). Genomic profiling and phenotypic indexing are urgently needed to identify elite landraces with desirable agronomic performance and nutritional profiles (21,37). The germplasm status, key crop wild relatives, major anti-nutritional factors, and commonly adopted mitigation methods for important minor pulses are summarized in Table 4.

Table 4. Overview of genetic resources and anti-nutritional traits of minor pulses

Crop	Germplasm Status (NBPGR)	Key wild species	Major Anti-nutritional Factors	Key Mitigation Methods	References
Rice bean	~2267 accessions	*V. dalzelliana, V. minima*	Phytates, tannins	Soaking, germination	(38,39)
Horse gram	~3194 accessions	*M. uniflorum var. stenocarpum*	Polyphenols, phytates	Cooking, sprouting	(38,39)
Moth bean	~1500 accessions	*V. trilobata*	Tannins, oligosaccharides	Soaking, fermentation	(38,40)
Adzuki Bean	~200 accessions	*Vigna angularis var. nipponensis*	Phytic acid, tannins, saponins	Soaking, germination, Roasting	(41,42)

5. Strategic Breeding Frameworks for Minor Pulses

To transform minor pulses from wild, semi-domesticated landraces into elite, uniform commercial varieties, breeders rely on an integrated pipeline of classical, mutational, and molecular breeding methodologies. Because these crops have historically been neglected by large-scale commercial breeding programs, the methodologies applied are uniquely tailored to handle challenges like high linkage drag, complex anti-nutritional traits, and a lack of homologous sequence data (43,44). Improving the nutritional profile of minor pulses is a central objective of modern breeding programs. Biofortification strategies aim to enhance essential nutrients such as protein, iron, zinc, selenium, and vitamins, while reducing anti-nutritional compounds like phytic acid and trypsin inhibitors (45,46). Combining biofortification with conventional, molecular, and participatory breeding approaches allows simultaneous improvement of yield, resilience, and nutritional quality. Hence, the combination of biofortification with advanced breeding approaches and new technologies can facilitate the development of nutritionally improved minor pulse varieties for addressing micronutrient malnutrition and supporting sustainable farming systems (47). The integrated breeding strategies employed for the genetic improvement of minor pulses are illustrated in Figure 1.

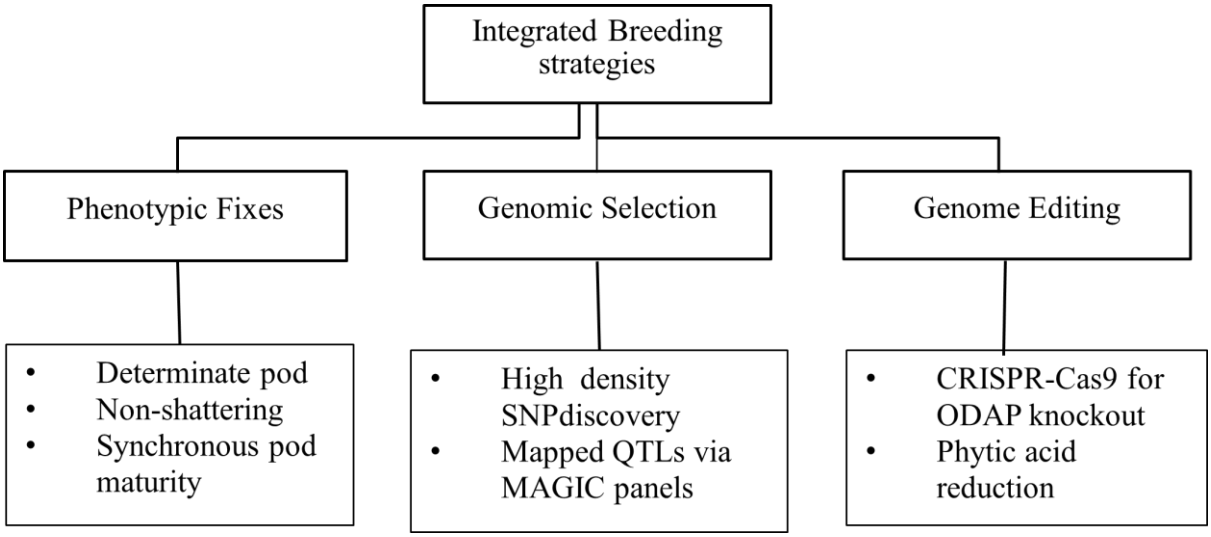

Fig.1. Integrated breeding strategies for genetic improvement of minor pulses

5.1 Conventional breeding

Traditional breeding methods, including hybridization, recurrent selection, and mutation breeding, remain important for minor pulses but are often limited by long generation times, small flowers, low pod set, and photoperiod sensitivity (43). Induced mutagenesis using physical agents (e.g., gamma radiation) and chemical mutagens (e.g., EMS, sodium azide) has generated variants with improved plant architecture, flowering time, yield components, and nutritional traits. Conducting multi-location trials is critical to assess genotype × environment interactions and identify varieties with stable performance across diverse conditions (21). The integration of conventional breeding, mutation approaches, and marker-assisted selection can accelerate genetic gains, particularly for complex traits such as drought tolerance and pest resistance.

5.2 Speed Breeding

Breeding cycles in minor pulses are long, and can only be grown for one or two generations per year due to seasonal constraints (48,49). In speed breeding, plants are cultivated within fully automated, enclosed growth chambers using extended photoperiods (typically 22 hours of continuous artificial LED light) and precise temperature/humidity cycling. This can substantially shorten the breeding cycle and increase the number of generations that can be produced annually, potentially accelerating variety development in horse gram and rice bean. The extended photoperiod, controlled temperature, and early seed harvest can accelerate flowering and seed production under controlled conditions (49).

When combined with early-generation genotyping, single-seed descent, and genomic selection, this approach accelerates the incorporation of desirable traits for yield, stress tolerance, and nutritional quality. Speed breeding is particularly advantageous for minor pulses, where conventional breeding is slow, facilitating the rapid development of climate-resilient and high-performing varieties (48,50,51). Overall, speed breeding serves as a valuable strategy to accelerate breeding cycles and facilitate the development of improved minor pulse cultivars with enhanced agronomic performance and nutritional quality.

5.3 Molecular Breeding

Recent advances in molecular breeding have greatly improved the potential for enhancing minor pulses using approaches such as marker-assisted selection (MAS), genome-wide association studies (GWAS), and genome editing (52,53). The availability of whole-genome sequences, high-throughput molecular markers, and QTL mapping facilitates accurate selection for important traits including stress tolerance, disease resistance, yield, and nutritional quality. Additionally, functional genomics and transcriptomic studies help clarify gene-trait relationships, enabling more targeted breeding approaches (54,55). When combined with high-throughput phenotyping and phenomics, these technologies improve selection efficiency, reduce breeding duration, and support the rapid development of climate-resilient and nutritionally improved minor pulse cultivars (55,56). Although still underutilized, horse gram (Macrotyloma uniflorum) has significant potential to contribute to nutritional security and climate adaptation.

Molecular markers are used to screen the seedlings at the DNA level, to identify the plants that inherits the specific trait of interest (22). Marker-Assisted Backcrossing (MABC) is deployed to transfer a single dominant gene (like a specific disease resistance gene) from a wild relative (donor parent) into an adapted local variety (recurrent parent) (50,51,53). By checking DNA markers at each backcross stage (BC_1–BC_4), breeders ensure the wild resistance gene is integrated while discarding the rest of the wild parent's unwanted DNA. This is a highly effective method for rapidly transferring the trait of interest into elite lines of minor pulses for improving nutritional quality.

5.4 Genomic-Assisted Selection and MAGIC populations

Transitioning from phenotypic selection to Genomic-Assisted Selection (GAS) is essential for accelerated genetic gains (31,50,51). High-throughput next-generation sequencing (NGS) platforms have enabled whole-genome sequencing (WGS) for crops like adzuki bean, grass pea, and moth bean (57,58). This sequencing simplifies high-density Single Nucleotide Polymorphism (SNP) discovery and the construction of ultra-high-density genetic linkage maps (59,60).

Furthermore, developing Multi-Parent Advanced Generation Intercross (MAGIC) populations by crossing multiple diverse parental lines helps to break the tight linkage drag. Traditional crosses mix only two parents, creating a narrow genetic base. Minor crops heavily leverage MAGIC panels to maximize genetic recombination (61,62). Breeders select 4 to 8 diverse founder parents representing distinct traits (e.g., high iron, drought tolerance, pod length). These parents are intercrossed in a highly structured, symmetrical web (diallel or funnel crossing scheme) over multiple generations until all founder genomes are thoroughly shuffled into stable, homozygous recombinant inbred lines (RILs) (62,63,64). MAGIC populations could be developed in minor Vigna species (rice bean and moth bean) to break tight, undesirable genetic linkages ("linkage drag") and accurately map Quantitative Trait Loci (QTLs) for complex yield-related traits like seed size, iron concentration, and drought tolerance indices (62,63,65).

5.5 Mutagenesis and Targeted Genome Editing (CRISPR/Cas9)

When a target trait such as zero-shattering pods or non-flatulence seed types does not exist anywhere within the available natural germplasm, breeders deliberately induce random mutations (66). Dry seeds are treated with physical mutagens (such as Gamma rays or Electron beams) or chemical mutagens (such as Ethyl Methane Sulfonate - EMS). The resulting M1 and M2 generations are rigorously screened for structural anomalies (47,66,67). Mutation breeding has been incredibly successful in grass pea (*Lathyrus sativus*) to create low-beta-ODAP mutant lines (67). It has also been applied to horse gram (*Macrotyloma uniflorum*) to alter its viny, spreading habit into a compact, erect plant structure ideal for mechanical harvesting (29,68).

When target traits display limited natural variance within accessible germplasm, induced mutation breeding and modern genome editing offer precise solutions (68,69) for eliminating anti-nutritional factors. CRISPR pipelines are also targeting fields like phytic acid biosynthesis (e.g., knocking out MIPS or IPK genes) and oligosaccharide pathways to systematically minimize anti-nutrients (70). This improves mineral bioavailability of Fe and Zn and eliminates gastrointestinal flatulence factors, removing major barriers to consumer adoption (70). Hence, integrating advanced molecular breeding techniques can enhance breeding efficiency and facilitate the rapid development of improved minor pulse cultivars adapted to changing agricultural conditions. Fig.2. summarizes the major improvement strategies, including processing methods and modern breeding approaches, used for enhancing underutilized pulses

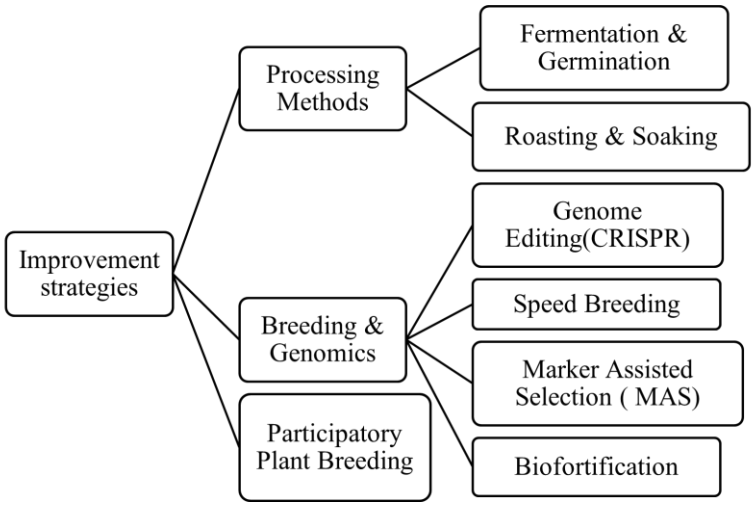

Fig.2. Improvement of underutilized pulses through various processing methods and modern plant breeding technique

6. Challenges, Constraints and Post-Harvest Bottlenecks

Beyond genetic limitations, minor pulses face significant post-harvest and structural hurdles that must be addressed to maximize their economic viability.

Hard-to-Cook (HTC) Defect: Minor pulses can develop a Hard-to-Cook phenomenon during storage under elevated temperatures and humidity (71). This structural defect lengthens necessary boiling times, increasing household fuel use and degrading nutritional value (71).

Low Mineral Bioavailability: Although rich in raw minerals, their nutritional value is often limited by high levels of anti-nutritional factors (ANFs), such as phytic acid and polyphenols, which chelate iron and zinc into insoluble complexes within the intestinal tract (22, 69).
Fragmented Supply Chains: The lack of minimum support pricing, centralized milling infrastructure, and specialized processing technologies limits minor pulses to local, unorganized markets (21).

7. Future Perspectives and Translational Research Horizons
To successfully transition minor pulses into global agri-food systems, research must focus on the following four interconnected pathways.
Pan-Genomics and Multi-Omics Integration: Constructing comprehensive pan-genomes for minor Vigna and Lathyrus species to chart the complete structural variation of these crops (58). Integrating transcriptomic, metabolomic, and proteomic datasets will help untangle the complex regulatory networks that govern stress tolerance and secondary metabolite synthesis (50).
Advanced Post-Harvest Processing: Scaling optimized processing methods such as solid-state microbial fermentation, controlled germination, and industrial extrusion cooking to deactivate anti-nutritional factors, eliminate the HTC defect, and optimize mineral bioavailability (39,40).
Developing Functional Food Ingredients: Isolating minor pulse proteins to formulate clean-label, hypoallergenic emulsifiers, texturized plant-based meat analogues, and gluten-free flour blends (72).
Policy Support and Agronomic Inclusion: Incorporating minor pulses into national agricultural policies, dryland intercropping initiatives, and institutional feeding programs (such as school lunches), while establishing reliable market channels for smallholder farmers (73).

8. CONCLUSION
Minor pulses are increasingly recognized as nutrient-dense and climate-resilient crops with immense potential to strengthen sustainable agriculture and ensure future food and nutritional security. Their rich nutritional composition, including proteins, minerals, dietary fibre, and bioactive compounds, emphasizes their value as functional foods with important health benefits. Furthermore, their ability to thrive under marginal environmental conditions and support sustainable farming practices highlights their significance in climate-resilient agriculture. Advances in breeding, genomics, biofortification, and processing technologies also provide promising opportunities to enhance their yield, nutritional quality, and overall utilization. Hence, promoting the conservation, genetic enhancement, and wider adoption of minor pulses can play a vital role in achieving sustainable food systems and long-term nutritional security.

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Authors' contributions
MJ conceptualized the study and prepared the original manuscript. DM critically reviewed and edited the manuscript. AT provided supervision and valuable suggestions. DA and LK reviewed the manuscript and contributed constructive comments. All authors read and approved the final manuscript.
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During the preparation of this work the I used Quillbot for grammar correction. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

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