

Nutritional and Antinutritional Factors in Underutilized Legumes: Occurrence, Nutritional Implications and Mitigation Strategies

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Abstract

Underutilized legumes offer significant opportunities to enhance global food and nutritional security under changing climatic conditions. These crops exhibit substantial potential due to their high protein content, valuable micronutrient composition and adaptability to marginal and low-input agricultural systems. However, their widespread utilization remains constrained by naturally occurring anti-nutritional compounds that interfere with nutrient absorption and, in some cases, pose health risks. This review synthesizes the current knowledge on the diversity, nutritional attributes, and anti-nutritional challenges of major underutilized legume species. This review examines the biochemical characteristics, distribution, and physiological effects of key anti-nutritional factors and their interactions with mineral bioavailability, protein digestibility, and metabolic responses. The effectiveness of pre-harvest interventions, household processing methods, industrial technologies, and emerging molecular and breeding approaches in mitigating anti-nutritional effects is critically evaluated in this review. Particular emphasis was placed on genotype environment interactions and their influence on nutrient antinutrient dynamics. This review identifies critical research gaps and future directions related to analytical standardization, large-scale validation, and human nutritional assessment. Overall, the findings underscore the need for integrated strategies that combine crop improvement, optimized processing, and nutritional evaluation to promote the safe utilization and commercial development of underutilized legumes in sustainable and nutrition-sensitive food systems.

Keywords: Underutilized legumes, anti-nutritional factors, nutrient bioavailability, mitigation strategies.

1. Introduction

Underutilized legumes, also known as neglected underutilized legume species, represent a diverse group of pulses. These crops have significant nutritional and agronomic potential but remain less cultivated, under-researched, and undervalued commercially (1). They primarily thrive in rain-fed, low-input, challenging agro-ecological areas, especially in South Asia and Sub-Saharan Africa. Their ability to resist drought, poor soil fertility, and temperature extremes, along with their biological nitrogen-fixing ability, plays a crucial role in sustainable dryland agriculture and climate-resilient food systems (1, 2).

Legumes like horse gram (*Macrotyloma uniflorum*), rice bean (*Vigna umbellata*), Bambara groundnut (*Vigna subterranea*), grass pea (*Lathyrus sativus*), winged bean (*Psophocarpus tetragonolobus*) are known for their high protein content and substantial mineral density. This highlights their potential to improve dietary diversity and nutritional security (3). Worldwide, food systems are dealing with both protein-energy malnutrition "hidden hunger." This term refers to the lack of essential micronutrients such as iron zinc, which especially affects those who rely on plant-based diets (4). Even with their beneficial nutritional profiles, the use of underutilized legumes is often limited by anti-nutritional compounds like phytates, tannins, protease inhibitors,

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lectins, non-protein amino acids. These compounds can affect mineral absorption and protein digestibility (5,6). In grass pea, the compound β -N-oxalyl-L- α , β -diaminopropionic acid (β -ODAP) has been linked to neurotoxicity when consumed excessively over long periods (7).

The coexistence of high nutrient density and significant anti-nutritional burden creates a bioavailability paradox, whereby a favorable biochemical composition does not necessarily translate into optimal physiological benefits. Therefore, this review critically examines the occurrence, variability, nutritional implications, and mitigation strategies of anti-nutritional compounds in underutilized legumes to enhance their safe and sustainable utilization in global food systems.

2. Underutilized Legumes: Diversity Nutritional Potential in Relation to Anti-Nutritional factors

2.1 Major Underutilized Legume Species

This review examines selected underutilized legume species exhibiting considerable variation in anti-nutritional compound composition, including horse gram (*Macrotyloma uniflorum*), Bambara groundnut (*Vigna subterranea*), grass pea (*Lathyrus sativus*), rice bean (*Vigna umbellata*), moth bean (*Vigna aconitifolia*), winged bean (*Psophocarpus tetragonolobus*), lablab bean (*Lablab purpureus*), and faba bean (*Vicia faba*) (3,8). These crops are predominantly cultivated under rain-fed and low-input agricultural systems across South Asia and sub-Saharan Africa, where their resilience to environmental stress supports subsistence farming and regional food security. Horse gram and moth bean are well-adapted to semi-arid environments with poor soil fertility and limited moisture availability, whereas Bambara groundnut maintains yield stability under nutrient-deficient soils. Grass pea demonstrates tolerance to drought and temporary flooding, enabling cultivation under extreme climatic conditions (9). Rice and lablab beans are commonly integrated into upland mixed cropping systems, whereas winged beans provide multiple edible plant parts, contributing to dietary diversification. Faba bean, despite its high protein content, contains anti-nutritional constituents such as tannins and vicine convicine complexes that influence nutrient utilization (11). Therefore, understanding species-specific variations in anti-nutritional compounds is essential for the safe dietary utilization and sustainable integration of these legumes into diversified food systems.

2.2 Nutritional Composition in Relation to Anti-Nutritional Interactions

Although underutilized legumes are nutritionally rich, their dietary value is significantly influenced by naturally occurring anti-nutritional compounds that affect nutrient digestion and absorption in the human body. Horse gram typically contains protein levels ranging between 20% and 25%, whereas grass pea and winged bean may exceed 25-30% protein on a dry weight basis (10).

However, the presence of protease inhibitors and tannin-protein interactions can reduce protein digestibility, despite a high total protein content. Mineral composition is another important nutritional attribute of these crops. Iron and zinc concentrations in Bambara groundnut and rice beans generally range from 4-9 mg/100 g and 2-5 mg/100 g, respectively (11). Nevertheless, phytates present in legume seeds form insoluble mineral complexes that reduce micronutrient bioavailability, indicating that nutritional quality depends more on mineral availability than on total mineral concentration. Dietary fiber fractions also include raffinose family oligosaccharides, which undergo microbial fermentation in the gastrointestinal tract when consumed in excess (6). Rice beans and horse gram, particularly pigmented genotypes, contain appreciable levels of phenolic compounds and condensed tannins that may impair protein utilization despite their antioxidant benefits (12). Similar anti-nutritional factors are reported in faba bean (*Vicia faba*), where tannins and phenolic constituents influence mineral utilization and protein digestibility (11). Grass pea represents a unique case due to the presence of β -ODAP, a neurotoxic amino acid associated with neurotoxicity under prolonged consumption (13), emphasizing the importance of evaluating nutritional benefits alongside anti-nutritional risks.

3 Anti-nutritional Compounds in Underutilized Legumes

Legumes synthesize various organic compounds through secondary metabolic pathways. These compounds are not directly related to plant growth and development but play significant roles in ecosystems. Secondary compounds are useful in allelopathic relationships, defending plants against herbivores, insects, and microorganisms, and in attracting pollinators, seed dispersal, and plant competition. However, some secondary compounds in legumes are toxic, unpalatable, or decrease the nutritional value of the plant for human consumption. These properties are due to the ability of these compounds to bind vital nutrients, inhibit metabolic functions, or interfere with digestion (14). These compounds are referred to as anti-nutritional factors (ANFs) or anti-nutritional compounds (ANCs). The major ANCs in legumes are enzyme inhibitors such as trypsin, chymotrypsin α -amylase inhibitors, lectins, tannins, phytic acid, oxalates, phenolic compounds, saponins and raffinose family oligosaccharides that induce flatulence. The levels of these anti-nutritional compounds (ANCs) also differ in legume seeds. Phytic acid and oligosaccharides, which are enzyme inhibitors, are mostly found in the cotyledons. However, most phenolic compounds, including tannins, are found in the seed coat (15). Recent studies have indicated that some compounds that were previously considered anti-nutritional may actually have nutritional benefits including acting as antioxidants in functional foods (16,17,18). Thus, knowledge of ANCs in legumes is essential for improving storage and processing techniques. This also helps enhance the use of legumes in the development of functional foods with sustainable nutrition.

Table 1: Major Anti-Nutritional Compounds in Underutilized Legumes, Their Sources, Effects, and Reduction Methods

Anti-Nutritional Compound	Chemical Nature / Class	Major Location in Seed	Principal Nutritional Effects	Representative Legumes	Major Reduction Methods
Phytic Acid (Phytates)	Phosphorylated inositol compound	Cotyledon	Binds Fe, Zn, Ca, Mg; reduces mineral bioavailability; inhibits digestive enzymes	Horse gram, Bambara groundnut, Rice bean, Winged bean	Soaking, Germination, Fermentation, Cooking
Oxalates	Organic acids (soluble and insoluble salts)	Cotyledon and seed tissues	Forms insoluble calcium complexes; reduces calcium absorption	Horse gram, Lablab bean, Bambara groundnut, Rice bean	Soaking, Germination, Cooking
Protease Inhibitors	Proteinaceous inhibitors (Kunitz, Bowman-Birk types)	Cotyledon storage tissues	Inhibits trypsin and chymotrypsin; reduces protein digestibility	Jack bean, Sword bean, Winged bean, Lablab bean	Boiling, Pressure cooking, Germination
Lectins (Phytohaemagglutinins)	Carbohydrate-binding glycoproteins	Seed storage tissues	Interferes with intestinal absorption; causes hemagglutination	Jack bean, Sword bean, Winged bean, Lablab bean	Soaking, Boiling, Thermal processing
Phenolic Compounds (Tannins)	Polyphenolic compounds	Seed coat (testa)	Forms protein-tannin complexes; reduces digestibility; imparts astringency	Horse gram, Moth bean, Rice bean, Bambara groundnut	Dehulling, Fermentation, Partial thermal treatment
Raffinose Family Oligosaccharides (RFOs)	Non-digestible carbohydrates (raffinose, stachyose, verbascose)	Cotyledon	Causes flatulence due to colonic fermentation	Bambara groundnut, Rice bean, Moth bean, Horse gram	Soaking, Germination, Fermentation
β -ODAP (Non-protein Amino Acid)	Neurotoxic amino acid derivative	Developing seeds	Induces neurolathyrism under prolonged consumption	Grass pea	Soaking, Boiling, Detoxification processing

3.1 Phytic Acid (Phytates)

Phytic acid or myo-inositol hexakisphosphate is the principal phosphorus-storage compound in legume seeds, accounting for approximately 60-80% of the total seed phosphorus, predominantly localized within the cotyledon tissues (15). Although essential for plant growth and seed germination, its strong affinity for mineral ions significantly influences nutrient availability in underutilized legumes used as protein sources. Structurally, phytic acid contains six phosphate groups that produce a high negative charge density, which enables binding with essential minerals, including iron, zinc, calcium, and magnesium. In the digestive system, the formation of insoluble phytate mineral complexes reduces mineral solubility and inhibits intestinal absorption despite the presence of adequate micronutrient concentrations in legumes. Phytate also interacts with proteins and digestive enzymes, such as trypsin and α -amylase, thereby limiting protein digestion and nutrient utilization (15). Species-specific studies have indicated considerable variation in phytate accumulation among underutilized legumes. Horse gram (*Macrotyloma uniflorum*) contains higher phytate levels ranging from 8.1-11.4 mg/g dry seed weight, reflecting efficient phosphorus storage under adverse agro-ecological conditions (20). Bambara groundnut (*Vigna subterranea*) exhibits concentrations of 6.5-9.8 mg/g depending on genotype and environment, while rice bean (*Vigna umbellata*) contains moderate levels of 5.2-7.6 mg/g. Winged beans (*Psophocarpus tetragonolobus*) also have appreciable phytate content, illustrating the nutritional anti-nutritional duality of these legumes (21). Phytate accumulation varies with genotype, soil phosphorus availability, and agronomic conditions, and although it restricts micronutrient bioavailability, it may exhibit antioxidant properties depending on dietary intake and processing practices (15).

3.2 Oxalates

Oxalates are naturally occurring organic acids present in several legume species, occurring either in soluble form or as insoluble calcium oxalate salts. In underutilized legumes, these compounds participate in physiological processes related to mineral regulation and plant defense; however, their nutritional significance arises from their ability to bind calcium and other divalent minerals, thereby reducing mineral availability in plant-based diets (15). The formation of insoluble calcium oxalate complexes within the gastrointestinal tract limits calcium absorption, despite the adequate mineral concentration in legume seeds. Species-specific investigations have demonstrated variability in oxalate accumulation among the underutilized legumes considered in this review. Horse gram (*Macrotyloma uniflorum*) contains appreciable oxalate levels, showing genotype dependence and variation with seed maturity stage, reflecting adaptation to stress-prone agro-ecological environments (20). Lablab bean (*Lablab purpureus*) exhibits moderate oxalate content influenced by seed structural composition and mineral storage characteristics, whereas comparatively lower concentrations have been reported in Bambara groundnut (*Vigna subterranea*) and rice bean (*Vigna umbellata*), with considerable accession- based variability across environments. Oxalate accumulation is further influenced by soil calcium availability, moisture stress, and agronomic practices regulating organic acid metabolism during seed development. Although generally present at lower concentrations than phytates, their combined effect may impair calcium utilization under frequent consumption conditions. Processing methods including soaking, germination and cooking significantly reduce oxalate levels thereby improving nutritional quality of underutilized legumes (15).

3.3 Protease Inhibitors

Protease inhibitors are major protein-related anti-nutritional compounds in underutilized legumes that reduce protein digestibility by inhibiting digestive enzymes such as trypsin and chymotrypsin. These inhibitors primarily occur as Kunitz-type and Bowman-Birke proteins, localized within cotyledon storage tissues, where they function as defense molecules against insect and microbial damage during seed development. Studies on underutilized legumes have demonstrated considerable interspecific variation in inhibitor activity. Jack bean (*Canavalia ensiformis*) exhibits high trypsin inhibitor activity exceeding 20-35 TIU mg⁻¹ protein indicating strong enzyme-binding capacity associated with storage protein fractions, while sword bean (*Canavalia gladiata*) shows comparable inhibitory levels, leading to reduced protein digestibility in raw seed flour preparations. Winged bean (*Psophocarpus tetragonolobus*), despite having a protein content above 30%, contains measurable inhibitor activity ranging from 12-18 TIU mg⁻¹, demonstrating that a high protein concentration does not ensure efficient utilization without processing. Lablab bean (*Lablab purpureus*) exhibits genotype-dependent variability in inhibitor activity between 8 and 15 TIU mg⁻¹, suggesting genetic regulation during seed maturation. Thermal processing significantly reduces inhibitor activity, with moist heat and boiling decreasing activity by 70-95%, whereas germination promotes proteolytic degradation, improving digestibility (15). Environmental stresses, including drought and nutrient limitation, may enhance inhibitor synthesis, indicating a strong genotype environment interaction that influences protein availability in climate-resilient underutilized legumes.

3.4 Lectins

Lectins, also referred to as phytohaemagglutinins, are a class of carbohydrate-binding glycoproteins widely distributed in underutilized legume seeds, where they primarily function as protective proteins against biotic stress factors. These proteins can selectively recognize and reversibly bind specific mono- or oligosaccharide residues on cell surface glycoproteins and glycolipids. Due to their hemagglutinating activity, lectins can cause erythrocyte agglutination and are therefore recognized as biologically active anti-nutritional compounds naturally occurring in several underutilized legumes (19). Legume lectins represent one of the largest groups of non-immune carbohydrate-binding proteins, predominantly localized within seed storage tissues. Following ingestion, lectins interact with receptor sites on intestinal epithelial membranes, where carbohydrate-mediated attachment to mucosal surfaces interferes with nutrient absorption. Such interactions may disrupt the digestive, absorptive, and secretory functions of the gastrointestinal tract, while prolonged exposure can influence epithelial cell turnover and membrane permeability, ultimately reducing nutrient utilization efficiency (19).

Among the species reviewed, jack bean (*Canavalia ensiformis*) contains the well-characterized lectin concanavalin A, which exhibits strong hemagglutinating activity and specificity toward mannose- and glucose-containing residues. Comparable activity has been reported in sword bean (*Canavalia gladiata*), whereas detectable lectin levels have been observed in winged bean (*Psophocarpus tetragonolobus*) and lablab bean (*Lablab purpureus*), with concentrations influenced by genotype and environmental conditions affecting seed biochemical composition (22). The structural stability of lectins depends on their association with calcium and transition metal ions, which are necessary for maintaining the active carbohydrate-binding conformation. Despite their anti-nutritional classification, lectins are highly heat-labile and are effectively inactivated through soaking and boiling, ensuring nutritional safety following the conventional processing of underutilized legumes (15).

3.5 Phenolic Compounds Condensed Tannins

Among the underutilized legumes reviewed, jack bean (*Canavalia ensiformis*) contains the well-characterized lectin concanavalin A, which exhibits strong hemagglutinating activity and high specificity toward mannose- and glucose-containing residues. Comparable hemagglutinating activity has also been reported in sword beans (*Canavalia gladiata*), while lectin concentrations have been detected in winged beans (*Psophocarpus tetragonolobus*) and lablab beans (*Lablab purpureus*), where accumulation varies according to genotype and environmental conditions influencing seed biochemical composition (22). The structural stability of lectins is maintained through association with calcium and transition metal ions, which are required to preserve the active carbohydrate-binding conformation. Despite their classification as anti-nutritional factors, lectins are highly sensitive to moist heat processing and are effectively inactivated through soaking and boiling, thereby ensuring the safe dietary utilization of underutilized legumes following conventional processing (15). Polyphenolic compounds, particularly tannins, further contribute to anti-nutritional limitations through the formation of tannin-protein and tannin-carbohydrate complexes that reduce macronutrient digestibility and suppress the activity of digestive enzymes involved in nutrient hydrolysis. Consequently, the mineral absorption efficiency and protein utilization decline in legume-based diets (24). Tannins also interfere with starch digestion by interacting with amylolytic enzymes and imparting bitterness and astringency, affecting palatability (25). Unlike many anti-nutritional compounds, tannins exhibit considerable thermal stability and may persist even after cooking. Elevated tannin concentrations have been reported in horse gram (*Macrotyloma uniflorum*) and moth bean (*Vigna aconitifolia*), whereas rice beans (*Vigna umbellata*) demonstrate strong genotype-dependent variations associated with seed coat pigmentation.

Bambara groundnut (*Vigna subterranea*) generally shows moderate phenolic levels, with darker-seeded genotypes accumulating higher tannin concentrations predominantly localized in the seed coat, explaining the association between testa color and anti-nutritional intensity (15,23). Moderate phenolic concentrations contribute to antioxidant and physiological benefits, highlighting the dual nutritional and anti-nutritional roles of these compounds in underutilized legumes.

3.6 Raffinose Family Oligosaccharides

Raffinose family oligosaccharides (RFOs) constitute an important group of soluble non-digestible carbohydrates that are widely distributed in underutilized legume seeds, where they function as reserve carbohydrates and osmoprotectants during seed maturation. The major oligosaccharides identified in legumes include raffinose, stachyose and verbascose, which are synthesized through the sequential galactosylation of sucrose during seed development. Although these compounds contribute to seed physiological stability, their nutritional relevance arises from their classification as flatulence-inducing anti-nutritional factors that influence gastrointestinal tolerance following legume consumption (11). Humans lack the endogenous enzyme α -galactosidase required for the hydrolysis of α -1,6-galactosidic linkages present in RFOs. Consequently, these carbohydrates escape digestion in the upper gastrointestinal tract and undergo microbial fermentation in the colon, producing gases such as hydrogen, carbon dioxide, and methane, leading to abdominal discomfort and reduced consumer acceptability, particularly in populations dependent on legumes as primary protein sources (6).

Among the underutilized legumes examined in this review, significant RFO accumulation has been reported in Bambara groundnut (*Vigna subterranea*), rice bean (*Vigna umbellata*), and moth bean (*Vigna aconitifolia*), while horse gram (*Macrotyloma uniflorum*) and lablab bean (*Lablab purpureus*) also contain measurable quantities, contributing to the characteristic flatulence associated with pulse-based diets. Genotypic and environmental variability strongly influence carbohydrate metabolism in climate-resilient legumes (3,8). Despite their anti-nutritional effects, RFOs exhibit prebiotic functionality by stimulating beneficial intestinal microbiota, including *Bifidobacterium* and *Lactobacillus* species. Therefore, modern processing approaches emphasize controlled reduction via soaking, germination, and fermentation rather than complete elimination to preserve their potential health benefits (6,12).

3.7 Toxic Non-protein Amino Acids: β -ODAP in Grass Pea

Among underutilized legumes, grass pea (*Lathyrus sativus* L.) represents a unique case in which nutritional resilience coexists with the naturally occurring toxic non-protein amino acid β -N-oxalyl-L- α , β -diaminopropionic acid (β -ODAP).

This compound accumulates primarily in developing seeds in association with nitrogen storage and stress adaptation metabolism, limiting wider utilization despite the crop's exceptional tolerance to drought, flooding, and poor soil fertility. Consequently, grass pea is often regarded as an "insurance crop" cultivated under extreme environmental conditions (26). β -ODAP induces neurotoxicity through excitotoxic overstimulation of glutamate receptors leading to degeneration of motor neuronal pathways and development of neurolathyrism characterized by irreversible lower-limb paralysis under prolonged dietary dependence (27,28).

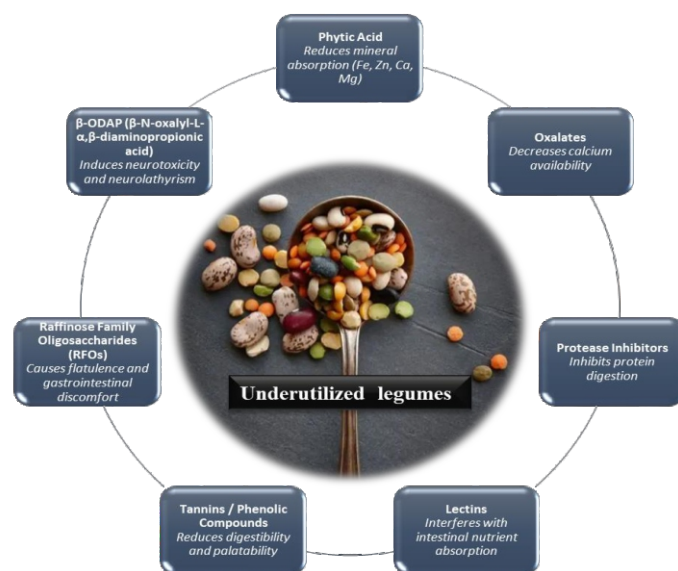


Figure 1: Major Anti-Nutritional Compounds in Underutilized Legumes and Their Nutritional Implications

Trypsin inhibitors inhibit the action of trypsin, an important enzyme responsible for protein breakdown in the body, thus affecting the bioavailability of essential amino acids (44). In grass pea, excessive consumption of β -ODAP, particularly under protein-deficient conditions, is linked to neurolathyrism, a motor neuron disorder characterized by spastic paralysis of the lower limbs. (32).

4.2 Beneficial Functional Properties

Tannins show strong antioxidant activity have been linked to a lower risk of chronic diseases such as cardiovascular diseases cancers due to their ability to scavenge free radicals, inhibit oxidative stress, modulate inflammation. Tannins have been shown to possess antimicrobial activity by inhibiting the growth of pathogenic bacteria fungi. Phytic acid has been shown to affect the gut microbial population by stimulating the growth of beneficial bacteria, hence promoting digestive health potentially improving nutrient absorption. It has anti-inflammatory properties that could help in the mitigation of inflammation-related disorders overall physiological well-being. It has strong antioxidant properties by scavenging free radicals inhibiting oxidative stress, hence potentially lowering the risk of chronic diseases such as cancer cardiovascular diseases.

Therefore, total eradication of all ANFs may not be nutritionally ideal; rather, optimal reduction strategies should focus on reducing inhibitory effects while preserving beneficial activities (44).

5. Management Mitigation Strategies for Anti-nutritional factors in Underutilized Legumes

Effective utilization of underutilized legumes requires targeted strategies to reduce anti-nutritional factors while maintaining nutritional value biological activity. Strategies for managing anti-nutritional factors in legumes can be generally classified into pre-harvest strategies, post-harvest processing methods, emerging biotechnological strategies that have been developed tested to improve nutritional availability reduce anti-nutritional factors in legumes (33,34).

5.1 Pre-Harvest Strategies

5.1.1 Breeding Approaches

Reduction of anti-nutritional factors is one of the major objectives of crop improvement programs for improving the quality nutritional status of produce. In this regard, various breeding methods such as conventional selection, mutation breeding, backcrossing, hybridization and population improvement have been used systematically to tap both natural induced genetic variability for the development of nutritionally superior varieties. Extensive screening of grass pea (*Lathyrus sativus*) accessions has shown large variability in β -ODAP levels, which has made it possible to identify develop low-toxin lines with as low as 0.074-0.109% levels, thus greatly reducing the risk of neurolathyrism (35).

5.2 Post-Harvest Processing

Similarly, genotypic variation in phytate content among Bambara groundnut horse gram accessions suggests potential for selecting low-phytate cultivars without compromising yield (36). Conventional breeding interspecific hybridization, along with recent advances in molecular breeding using SSR SNP markers, marker-assisted selection, genome-wide association studies, have improved the accuracy efficiency of breeding low anti-nutritional factor genotypes. Moreover, translational genomics has made it possible to move desirable alleles for low anti-nutritional content adaptability from one legume species to another (37).

5.1.2 Agronomic Management

Environmental factors are major determinants of the concentration of anti-nutritional compounds in legumes, agronomic practices offer effective ways of managing these compounds. Phosphorus availability in soil, in particular, influences phytate production, since phytate is the main form of phosphorus storage in seeds is directly associated with phosphorus metabolism in plants (38, 39). Effective fertilizer water management can indirectly help manage phenolic protease inhibitor contents by affecting plant nutrient uptake stress physiology (35). Moreover, the phenolic content of legumes such as horse gram (*Macrotyloma uniflorum*) can be affected by the time of harvest, as the plant's maturity stage affects the biochemical pathways involved in the production of anti-nutrients (40). Thus, an effective crop management approach can help in the reduction of anti-nutritional factors in underutilized legumes.

Post-Harvest Processing Techniques for Reducing Anti-Nutritional Factors in Legumes

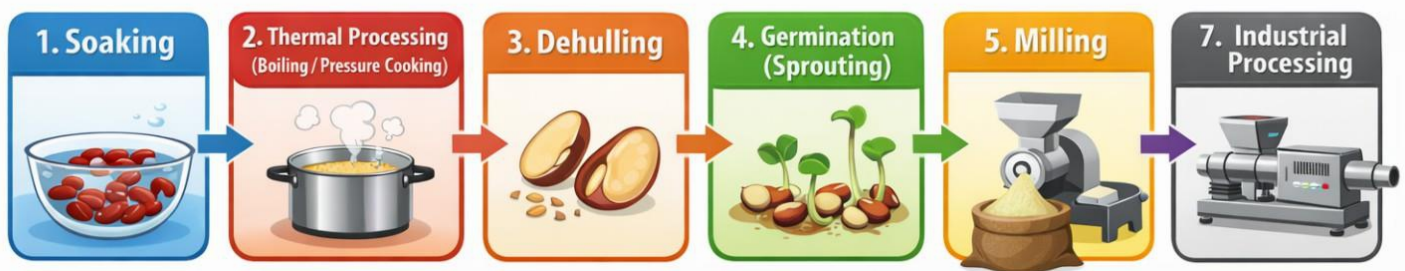


Figure 2. Post-Harvest Processing Techniques for Reducing Anti-Nutritional Factors in Legumes

5.2.1 Soaking

Soaking is a common pre-processing method that has been found to play an important role in the reduction of anti-nutritional factors in legumes by facilitating the movement of water-soluble compounds into the soaking liquid, thus improving the bioavailability of nutrients. It has been observed that soaking kidney beans for 12 hours can decrease trypsin inhibitor activity by about 18% (40). In addition, soaking legume seeds for 8-24 hours has been observed to decrease the levels of tannins phytic acid by 20-45% 15-35%,

respectively, while also reducing the levels of flatulence-causing oligosaccharides, thus improving the nutritional quality (41). However, the soaking process can be affected by seed coat permeability, soaking time, water:seed ratio, thus the need for optimized soaking processes to improve nutritional quality(5).

5.2.2 Thermal Processing

Thermal processing techniques like boiling pressure cooking can greatly improve the nutritional value digestibility of

legumes by inactivating heat labile anti-nutritional factors, especially trypsin inhibitors, lectins, phenolic compounds (42). It has been observed that thermal processing can reduce protease inhibitor activity by as much as 100% tannin content in various varieties of pulses, thus improving protein digestibility (43,44). Moreover, cooking helps in protein denaturation the leaching of phytic acid other soluble anti-nutrients into the cooking liquid, thus improving the nutritional value (42).

5.2.3 Dehulling

Dehulling, a major processing procedure, entails the physical removal of the outer covering of seeds, such as the husk or pericarp, which are rich in various antinutritional components. The physical separation technique aims at the removal of the pericarp or testa, which is often fibrous antinutrient-rich, may contain compounds such as tannins phytates, thus improving the nutritional availability of the legume cotyledonary matter (6). For example, the reduction of phytic acid in certain underutilized legumes was shown to range from 20% to 45% after dehulling, depending on the processing time type of legume (40).

5.2.4 Germination

Germination is a metabolic process triggered by the absorption of water in seeds, resulting in the activation of enzymes that degrade stored macromolecules to produce energy for seedling growth, which has a significant effect on the concentration of antinutritional compounds (45). Germination has been shown to cause a significant reduction in the phytic acid content, resulting in improved mineral availability and absorption in germinated legumes, making them more nutritious. Germination triggers the activation of endogenous proteases, which causes the degradation inactivation of lectins, thereby improving the digestibility safety of legumes. Tannins, which are major phenolic anti-nutrients in legumes, inhibit protein digestibility adversely affect organoleptic properties; however, germination significantly reduces their concentration, thereby enhancing the acceptability nutritional quality of germinated legumes (29).

5.2.5 Milling

Milling is a mechanical operation that can reduce the size of the particles of grains legumes, mainly converting them into flour, which can have a significant effect on their anti-nutritional factors and nutritional availability (5). Milling techniques are very important in determining the functional analytical characteristics of legume flour. Pin-disc roller milling are mainly used for the production of flours with defined particle size functionality for protein extraction, micro-structure analysis, pasting property analysis. On the other hand, ultra-centrifugal milling is used for the production of fine uniform-sized flours, which are mainly used for enzyme activity analysis volatile compound analysis.

Thus, the selection of milling technique is very important for the accurate analysis of the quality of legume flour (46).

5.2.6 Fermentation

Fermentation is a natural process of decomposition whereby complex organic substrates are converted into simpler compounds by the action of microorganisms (47). Fermentation increases the degradation of antinutrients such as phytates and other complex compounds by the action of microorganisms, hence improving the digestibility of proteins bioavailability of minerals. Studies on fermented legumes, including Bambara groundnut, has shown that the degradation of phytate- mineral complexes protein-bound antinutrients during fermentation is a major factor in improving nutritional quality (49, 50).

5.2.7 Industrial Processing

Extrusion cooking is a highly advanced HTST processing technology that effectively counteracts anti-nutritional factors in legume-based products through the combined action of heat energy, mechanical shear force, pressure. This process causes a large number of physicochemical changes, such as starch gelatinization, protein denaturation, disruption of cellular matrices.

(49). Extrusion cooking has been widely documented as an effective processing method for reducing multiple anti-nutritional factors in legumes such as tannins, phytic acid, trypsin inhibitors, lectins, simultaneously enhancing the digestibility of starch proteins overall nutritional value. (50). The degree of anti-nutrient destruction is highly dependent on processing variables such as barrel temperature, feed moisture content, screw speed, residence time, thus emphasizing the extreme importance of accurate optimization of processing conditions(49). Autoclaving, a very effective thermal processing technique, makes use of steam under pressure to reduce a wide spectrum of antinutritional compounds in plant-based foods to a great extent, thus improving the nutritional bioavailability safety of the food for consumption(5,51). studies revealed that autoclaving can reduce anti-nutritional factors in legumes to a great extent, many studies have shown higher levels of reduction of these factors compared to conventional processing techniques (5).

5.3 Emerging Technologies

Recent breakthroughs in molecular biology have significantly enhanced the accuracy efficacy of approaches designed for the modification of anti-nutritional pathways in legumes. Various studies have shown that the CRISPR/Cas system of genome editing can be utilized effectively for the disruption of the genes involved in the biosynthesis of phytate, recent evidence suggests that similar molecular approaches can be used to limit the accumulation of β -ODAP in grass pea. (36,52,53). At the same time, omics-based breeding strategies, which combine genomic, transcriptomic, metabolomic information, can be used to identify regulatory

associations related to phenolic metabolism storage protein interactions, thus enabling more targeted approaches for crop improvement. Although these modern approaches have great potential, they must be carefully evaluated to avoid any unintended agronomic nutritional trade-offs. Recent advances in molecular biology provide opportunities to precisely manipulate anti-nutritional pathways. CRISPR/Cas gene editing has potential for targeted modification of genes involved in phytate biosynthesis β -ODAP accumulation (36, 53). Omics-assisted breeding approaches enable identification of candidate genes regulating phenolic metabolism storage protein interactions (36, 53)

6. Research Gaps Future Perspectives

Significant progress has been made in understanding anti-nutritional factors in legumes ways to reduce them using traditional new processing methods. However, several important research gaps still exist. Most studies focus on single processing techniques, with few comparisons across different underused legume species their specific anti-nutrient profiles. This limits the development of improved, crop-specific solutions (32,35). Furthermore, current research mainly remains in laboratory settings. Systematic studies on how to scale up, ensure economic viability, gain consumer acceptance of processed legume products are lacking (6,5). Additionally, there are few thorough assessments of genetic diversity its connection to anti-nutrient buildup. This limits breeding efforts aiming to enhance nutritional quality (29). Future research should focus on combining processing studies, genomics-supported crop improvement, standardized analytical methods and assessments of the value chain. These multidisciplinary approaches are crucial for creating nutritionally improved, safe, marketable legume-based foods, while also promoting the sustainable use of underused legumes in food nutrition security.

7. Conclusion

Underutilized legumes remain an insufficiently exploited resource for improving nutrition, climate resilience, and sustainable farming systems. Their high protein content, valuable mineral composition, and adaptability to marginal growing conditions highlight their potential to support diverse and resilient food systems. However, their wider utilization is constrained by the presence of anti-nutritional factors, which affect nutrient absorption, protein digestion, and food safety. The occurrence and concentration of these compounds vary across species, genotypes, and environments, while some also exhibit beneficial antioxidant and metabolic properties, emphasizing the need for balanced risk benefit evaluation. Addressing these challenges requires integrated strategies involving genotype selection, optimized agronomic practices, traditional and modern processing techniques, and emerging molecular approaches. Household-level interventions provide immediate benefits, whereas breeding and gene-editing technologies offer

sustainable long-term solutions. Future progress will depend on standardized analytical methods, multi-location studies, and human bioavailability assessments. Achieving a scientifically informed balance between reducing anti-nutritional constraints and preserving beneficial properties is essential for unlocking the full potential of underutilized legumes in nutrition-sensitive and sustainable food systems.

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