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Review of Processing, Anti-Nutritional Factors Reduction and Nutrient Bioavailability in Selected Legumes

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ABSTRACT

Legumes such as lablab (*Lablab purpureus*), common bean (*Phaseolus vulgaris*) and cowpea (*Vigna unguiculata*) are essential dietary sources of protein, complex carbohydrates and micronutrients, while also contributing to sustainable agriculture through nitrogen fixation. However, their nutritional potential is often limited by anti-nutritional factors (ANFs) including phytates, tannins, lectins and oligosaccharides, which can impair nutrient bioavailability and digestibility. This review provides a comparative assessment of ANF profiles in lablab (*Lablab purpureus*), common bean (*Phaseolus vulgaris*) and cowpea (*Vigna unguiculata*) and examines strategies for mitigating these compounds through traditional methods such as soaking, boiling, germination and fermentation, as well as modern approaches including controlled microbial fermentation, extrusion cooking and enzymatic or chemical treatments. Evidence indicates that processing conditions such as soaking duration, fermentation type and temperature significantly influence ANF reduction, nutrient retention and sensory attributes across these legumes. For instance, sprouting in cowpeas preserves heat-sensitive vitamins, while controlled fermentation in lablab improves protein digestibility and reduces oligosaccharides. Overall, integrating traditional and modern processing techniques offers effective strategies to enhance bioavailability, improve sensory quality and expand the dietary and industrial utilization of these legumes, supporting sustainable, nutrient-rich, plant-based diets globally.

1 | Introduction

Legumes belonging to the Fabaceae family, including lablab (*Lablab purpureus*), common bean (*Phaseolus vulgaris*) and cowpea (*Vigna unguiculata*), constitute a cornerstone of global food security and human nutrition (Broughton et al. 2003; FAO 2022). These crops are recognized not only for their high-quality proteins, complex carbohydrates and essential micronutrients such as folate, iron, magnesium and zinc but also for their agronomic benefits, including biological nitrogen fixation and soil fertility enhancement (Broughton et al. 2003; Campos-Vega et al. 2010). Their incorporation into diets is increasingly recommended to mitigate chronic diseases due to their low glycaemic index (GI), high dietary fibre content and favourable lipid profiles, positioning legumes as central components of sustainable, plant-based dietary patterns (USDA 2025).

Despite their nutritional and ecological significance, the utilization of these legumes is constrained by anti-nutritional factors (ANFs), bioactive compounds that interfere with protein digestibility, mineral absorption and carbohydrate metabolism. The principal classes of ANFs encompass phytates, tannins, lectins, saponins, enzyme inhibitors and raffinose-family oligosaccharides, each characterized by distinct

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biochemical properties and varying degrees of heat stability (Gilani et al. 2012). While these compounds confer evolutionary advantages in plant defence mechanisms, they may induce gastrointestinal discomfort, reduce nutrient bioavailability and pose potential toxicity risks when legumes are consumed raw or inadequately processed (Guce et al. 2009; Leech 2019). Notably, the composition and concentration of ANFs differ among species: Lablab (*Lablab purpureus*) is particularly rich in oligosaccharides and phenolic compounds; cowpea (*Vigna unguiculata*) contains comparatively higher levels of trypsin inhibitors; and common bean (*Phaseolus vulgaris*) exhibits elevated phytate and lectin concentrations. These interspecific differences underscore the necessity for species-specific mitigation strategies.

Mitigation of ANFs can be achieved through both traditional and modern processing techniques. Traditional household practices including soaking, boiling, sprouting and spontaneous fermentation have demonstrated efficacy in reducing specific ANFs while largely preserving nutritional quality. Contemporary approaches, such as controlled microbial fermentation, extrusion cooking, enzymatic treatment and chemical modification, apply scientific precision to enhance ANF reduction and improve nutrient bioavailability (Samtiya et al. 2020; Yi et al. 2021). However, optimization is essential, as certain processing methods, while effective in lowering ANFs, may inadvertently degrade heat-sensitive vitamins or alter sensory attributes, thereby influencing consumer acceptance.

This review provides a comparative analysis of ANF profiles in lablab (*Lablab purpureus*), common bean (*Phaseolus vulgaris*) and cowpea (*Vigna unguiculata*), emphasizing how traditional and modern processing strategies can be tailored to each species to maximize nutrient bioavailability while maintaining organoleptic quality. By synthesizing existing evidence, this article identifies knowledge gaps, species-specific responses and practical recommendations for enhancing the utilization of these legumes as nutrient-dense, sustainable and culturally acceptable foods. Unlike prior reviews that focus on individual legumes or isolated processing methods, this study presents a comparative, species-specific synthesis integrating nutritional outcomes, processing efficiency, sensory quality and adoption pathways within sustainable agronomic systems.

2 | Review Design and Literature Search

2.1 | Review Design

This review adopted a thematic, integrative approach to critically analyse literature on lablab (*Lablab purpureus*), with particular emphasis on its anti-nutritional factors (AFN), their occurrence, mitigation strategies and implications for adoption among smallholder farmers in Africa. Following the first introduction of the term anti-nutritional factors (AFN), the abbreviation AFN is used consistently throughout this review. The integrative review design was selected because it enables the synthesis of diverse empirical and theoretical studies, thereby generating new conceptual frameworks, perspectives and actionable insights on complex topics (Whittemore and Knafl 2005; Torraco 2016). Unlike methodological or bibliometric reviews, this approach prioritizes analytical interpretation over quantitative aggregation, facilitating a nuanced understanding of how AFN influence lablab processing, utilization and adoption pathways. The thematic structure, complemented by a Strengths, Weaknesses, Opportunities and Threats (SWOT) analytical framework, enabled the consolidation of dispersed evidence into a coherent and logically connected narrative. This framework supports the identification of research gaps, technological innovations and strategic opportunities to enhance lablab's role in sustainable food and nutrition systems (Benzaghta et al. 2021). The approach aligns with the review's objective of evaluating strategies for AFN mitigation and translating scientific findings into practical interventions aimed at strengthening lablab's contribution to food and nutritional security, particularly within dryland farming systems across Africa (Torraco 2016; Snyder 2019).

2.2 | Literature Search

An extensive desk-based literature search was conducted between January and July 2025 across multiple scholarly databases, including Scopus, Web of Science, CAB Abstracts, AGRIS and Google Scholar, complemented by grey literature from institutional repositories such as FAO, CGIAR and national agricultural research systems. Using multiple databases ensured comprehensive coverage and minimized publication bias by integrating both peer-reviewed and institutional sources, as recommended for integrative and thematic reviews (Snyder 2019; Whittemore and Knafl 2005). Scopus and Web of Science were selected for their broad multidisciplinary coverage and high-impact indexing, while CAB Abstracts and AGRIS were particularly suitable for agricultural and biological sciences, including tropical and smallholder-focused research (Bramer et al. 2017). Google Scholar and institutional repositories were included to capture grey literature, theses and reports that are often excluded from commercial databases but highly relevant for context-specific agricultural issues in Africa (Paez 2017). To ensure comprehensive coverage, the review did not impose restrictions on publication year, thereby allowing inclusion of both foundational and contemporary studies. This approach captured research advances across lablab, cowpea and common bean, including their nutritional and anti-nutritional profiles, mitigation strategies, agronomic performance and adoption dynamics among smallholder farmers. The inclusive approach incorporated diverse study designs experimental, breeding, agronomic, nutritional and adoption-focused providing a holistic understanding of the potential, limitations and practical applications of these legumes in sustainable dryland systems. Overall, this narrative and integrative methodology allowed the review to move beyond mere description towards an actionable synthesis, linking biochemical evidence with practical adoption considerations. The findings provide a foundation for informed breeding, processing and policy interventions aimed at enhancing the utilization and adoption of lablab, cowpea and common bean in smallholder farming systems.

3 | Antinutritional Factors in Lablab, Common Bean and Cowpea

The consumption of legumes is frequently associated with the presence of anti-nutritional factors (ANF), naturally occurring compounds synthesized through secondary metabolism. These metabolites are not directly essential for plant growth but serve protective and ecological functions, including defence against herbivory, inhibition of pathogen infection and contribution to allelopathic interactions within the environment (Kumar et al. 2021). Although non-toxic to the plant itself, ANF may reduce nutrient availability and induce adverse physiological effects in humans and animals when consumed in substantial quantities (Gemede et al. 2014).

ANF in legumes are commonly classified based on thermal stability into heat-stable and heat-labile compounds. Heat-stable ANF such as phytic acid, condensed tannins, saponins and certain alkaloids are resistant to thermal degradation and may persist following conventional cooking or processing. In contrast, heat-labile ANF including lectins, cyanogenic glycosides and protease inhibitors are sensitive to elevated temperatures and can be largely inactivated through boiling, roasting or other thermal treatments (Kyriazakis and Whitemore 2006).

From a biochemical standpoint, ANF can also be categorized as proteinaceous and non-protein compounds. Protein-based ANF, such as lectins and protease inhibitors, interfere with digestive enzymes and impair protein utilization. Non-protein ANF including tannins, phytic acid, oxalates and saponins primarily reduce mineral absorption and affect carbohydrate and protein digestibility (Soetan and Oyewole 2009). These compounds are unevenly distributed within seed structures: Phytic acid, oligosaccharides and enzyme inhibitors are predominantly localized in the cotyledons, whereas tannins and other polyphenolic compounds are concentrated in the seed coat (Duenas et al. 2002; Reddy et al. 1985).

In lablab (*Lablab purpureus*), common bean (*Phaseolus vulgaris*) and cowpea (*Vigna unguiculata*), the presence and concentration of ANF vary considerably depending on species, genotype, and environmental conditions. For example, lectins and trypsin inhibitors are relatively more abundant in common bean, necessitating thorough thermal processing to ensure safety. In contrast, oligosaccharides and saponins are comparatively higher in cowpea and lablab, which may contribute to gastrointestinal discomfort when consumed in excess (Bouzier et al. 2023). Despite their potential to reduce nutrient bioavailability, certain ANF such as saponins and phytic acid also exhibit beneficial bioactivities, including antioxidant, cholesterol-lowering and anti-carcinogenic properties. These dual roles have stimulated interest in their application in functional foods and nutraceutical development (Bouzier et al. 2023; Abulkalam 2002). Understanding the types, distribution and physiological effects of ANF in these legumes is therefore essential for ensuring food

TABLE 1 | Major anti-nutritional factors (ANF) identified in lablab, common bean and cowpea, their seed localization and associated nutritional implications.

Anti-nutritional factor (ANF)	Legume species	Seed location	Effect/disadvantage	References
Phytates	Lablab, common bean, cowpea	Cotyledon	Chelates minerals (Zn, Fe, Ca, Mg), reducing bioavailability	Gupta et al. 2013
Condensed tannins	Lablab, common bean, cowpea	Seed coat	Reduces protein digestibility and starch utilization via enzyme inhibition	Gemede et al. 2014
Saponins	Lablab, cowpea, common bean	Cotyledon and seed coat	Forms complexes with proteins/minerals; may cause bitterness and mild gastrointestinal irritation at high doses	Bouzier et al. 2023
Lectins (haemagglutinins)	Common bean, cowpea, lablab	Cotyledon	Binds to gut epithelial cells, inhibits nutrient absorption, may cause nausea, diarrhoea and allergic reactions	Adamcova et al. 2021
Protease inhibitors (Kunitz and Bowman–Birk)	Common bean, cowpea, lablab	Cotyledon	Inhibits digestive enzymes, reduces protein digestibility	Savage et al. 2003
Oxalates	Lablab, common bean, cowpea	Cotyledon and seed coat	Forms insoluble complexes with Ca, Mg, Fe, reducing mineral absorption	Siener et al. 2021
α-Amylase inhibitors	Common bean, cowpea	Cotyledon	Inhibits starch digestion, reducing energy availability	Gemede et al. 2014
Cyanogenic glycosides	Lablab (minor), cowpea (trace)	Cotyledon	May release toxic HCN if improperly processed	Samtiya et al. 2020

safety while optimizing nutritional quality. Processing techniques including soaking, fermentation, sprouting and thermal treatment are widely employed to reduce ANF concentrations while preserving desirable nutrients. Table 1 summarizes the major ANF identified in lablab, common bean and cowpea, their seed localization, associated physiological effects and nutritional implications.

4 | Preparation and Processing Techniques

The adverse effects of ANFs in legumes such as common bean (*Phaseolus vulgaris*), cowpea (*Vigna unguiculata*) and lablab (*Lablab purpureus*) can be significantly reduced through appropriate preparation and processing techniques (Samtiya et al. 2020) and (Tables 2, 3 and 4). While food preparation is often considered a preliminary step before industrial processing, it independently plays a crucial role in mitigating ANFs and improving nutrient bioavailability. These techniques are broadly categorized into traditional and modern processing methods. Traditional processing methods, developed through indigenous knowledge systems and passed down across generations, include soaking, boiling, cooking, germination (sprouting) and spontaneous fermentation. These methods are widely practiced at household and community levels due to their low cost, simplicity and accessibility. Modern processing techniques, in contrast, are scientifically designed and technologically driven, often requiring controlled conditions and specialized equipment. These include controlled microbial fermentation, extrusion cooking, enzymatic hydrolysis and chemical modification of legume constituents. The selection of an appropriate processing method depends on several factors, including legume species, type and concentration of ANFs, desired level of reduction, product use, processing cost, equipment availability and

TABLE 2 | Effect of soaking, soaking solutions and boiling on the nutritional composition of common bean.

Parameter	Unprocessed beans (Control)	Distilled water soaking (12 h)	Na_2CO_3 soaking (12 h)	Distilled water soaking (12 h) + boiling	Na_2CO_3 soaking (12 h) + boiling
Moisture (%)	11.71 ± 0.02	ND	ND	ND	ND
Ash (%)	3.97 ± 0.01	3.70 ± 0.01	3.67 ± 0.01	2.48 ± 0.01	2.48 ± 0.01
Dry matter (%)	88.29 ± 0.05	50	100	100	46
Crude protein (%)	21.02 ± 0.01	22.37 ± 0.01	23.01 ± 0.01	24.08 ± 0.01	24.80 ± 0.01
Crude fibre (%)	3.60 ± 0.00	3.70 ± 0.01	3.89 ± 0.05	5.10 ± 0.01	4.21 ± 0.05
Crude fat (%)	1.20 ± 0.01	1.08 ± 0.01	1.18 ± 0.01	0.95 ± 0.01	1.20 ± 0.01
Carbohydrates (%)	62.09 ± 0.03	72.83 ± 0.01	72.13 ± 0.01	72.48 ± 0.02	71.51 ± 0.02

Source: Adapted from Qureshi et al. (2020).

TABLE 3 | Effects of soaking and boiling on raffinose family oligosaccharides in common bean.

Treatment	Raffinose (mg/100 g)	Reduction (%)	Stachyose (mg/100 g)	Reduction (%)
Raw beans (control)	414.83 ± 8.96	—	1702.01 ± 31.09	—
Unsoaked, boiled	193.45 ± 9.17	52	1011.70 ± 18.70	41
16 h soaked (DW) + boiling	106.24 ± 7.28	75	803.86 ± 18.74	53
16 h soaked (Na_2CO_3) + boiling	78.28 ± 6.68	81	618.96 ± 16.70	60

Source: Adapted from Jepleting et al. (2025).

TABLE 4 | Effect of soaking and boiling on anti-nutritional factors in common bean.

Anti-nutritional factor (mg/100 g)	Control	Soaked (DW, 12 h)	Soaked (DW, 12 h) + boiling	Soaked (Na_2CO_3 12 h)	Soaked (Na_2CO_3 12 h) + boiling
Phytates	630.91 ± 0.20	629.05 ± 0.61	616.00 ± 0.87	591.24 ± 0.71	454.62 ± 0.51
Tannins	713.94 ± 0.05	300.05 ± 0.08	179.73 ± 0.21	230.05 ± 0.14	94.17 ± 0.09
Saponins	93.09 ± 0.54	70.35 ± 0.20	10.52 ± 0.19	39.75 ± 0.08	4.54 ± 0.27

Source: Adapted from Qureshi et al. (2020).

consumer preferences (Barakat et al. 2023). Beyond ANF reduction, these processing techniques also aim to improve sensory quality, palatability, shelf life, texture and flavour, thereby enhancing consumer acceptability and market potential (Yi et al. 2021).

4.1 | Traditional Processing Techniques

4.1.1 | Soaking

Soaking is one of the most widely applied traditional techniques for legumes such as common bean, cowpea and lablab. Initially adopted to reduce cooking time, soaking is now recognized for its effectiveness in lowering ANFs through leaching of water-soluble compounds and activation of endogenous enzymes. The efficiency of soaking depends on duration, temperature, soaking medium and seed coat permeability. Studies consistently show that longer soaking durations (12–48 h) result in greater reductions of phytates, tannins, oxalates and oligosaccharides, although excessive soaking may promote nutrient losses and microbial growth (Adebayo et al. 2014). For most legumes, overnight soaking (≈12 h) represents an optimal balance between ANF reduction and nutrient retention (Siddhuraju et al. 2001). Discarding soaking water is strongly recommended, as it contains leached raffinose-family oligosaccharides responsible for flatulence.

4.1.2 | Boiling and Cooking

Boiling remains the dominant cooking method for legumes worldwide. Heat treatment effectively inactivates heat-labile ANFs, including lectins, protease inhibitors and α-amylase inhibitors, through protein denaturation (Kinyanjui et al. 2015). In common beans, cowpeas and lablab, boiling temperatures of approximately 96°C–100°C significantly reduce ANFs while improving starch digestibility and protein availability.

4.1.3 | Spontaneous Fermentation and Germination

Spontaneous fermentation relies on naturally occurring microorganisms and is common in traditional legume foods. Although less predictable than controlled fermentation, it enhances mineral bioavailability and sensory attributes by degrading phytates and oligosaccharides (Adebo et al. 2020). Germination (sprouting), particularly relevant for cowpea and lablab, activates endogenous enzymes such as phytase and α-galactosidase, leading to marked reductions in phytates and flatulence-causing sugars while preserving heat-sensitive vitamins.

4.2 | Modern Processing Techniques

Controlled fermentation, extrusion cooking and chemical modification represent advanced approaches for mitigating ANFs while maintaining functional and structural integrity. Extrusion cooking, in particular, is highly effective in reducing tannins, phytates, protease inhibitors, oxalates and saponins through combined heat, pressure and shear forces (Kaur et al. 2015). These methods are increasingly applied in the development of legume-based meat analogues, fortified foods and nutraceutical products, including those derived from common bean, cowpea and lablab.

5 | Impact of Processing on Selected Legumes

5.1 | Effect of Soaking and Boiling on Nutritional and Anti-Nutritional Properties of Common Bean (*Phaseolus vulgaris*)

Soaking and boiling are the most widely applied household processing techniques for common beans, primarily intended to reduce cooking time. However, substantial evidence shows that these practices also improve nutritional quality and significantly reduce anti-nutritional factors (ANFs). The effectiveness of soaking depends on multiple interacting variables, including the soaking medium, solution composition, duration, temperature, bean variety, seed integrity and intended downstream processing such as cooking, fermentation, sprouting, or industrial utilization. Alkaline soaking solutions, particularly sodium carbonate (Na_2CO_3), have received considerable attention due to their capacity to accelerate hydration, soften seed tissues and enhance ANF reduction. These effects are mediated through increased pH, which promotes cell wall loosening and pectin solubilization, thereby facilitating leaching and thermal degradation during subsequent cooking.

Soaking alone resulted in only marginal changes in crude protein content (Table 2), increasing from 21.02% in the control to 22.37% and 23.01% after distilled water and Na_2CO_3 soaking, respectively. This limited change suggests that storage globulin proteins in common bean are structurally stable and not substantially solubilized or degraded during hydration. However, soaking followed by boiling increased the apparent protein concentration to 24.08% (distilled water) and 24.80% (Na_2CO_3). This increase does not necessarily indicate protein synthesis but rather reflects a relative concentration effect resulting from dry matter loss, particularly through leaching of soluble carbohydrates and minerals into the soaking and cooking media (Wang et al. 2008). Additionally, thermal denaturation during boiling may improve protein digestibility by unfolding globular structures and enhancing enzyme accessibility, thereby increasing measurable protein availability. Fibre content increased after cooking, likely due to the relative concentration effect following starch gelatinization and solubilization of non-fibre components.

The greatest reduction in raffinose and stachyose was achieved through alkaline soaking followed by boiling, driven by combined leaching, thermal breakdown and activation of endogenous α-galactosidase enzymes that hydrolyse oligosaccharides into digestible sugars (Han and Baik 2006; Oboh et al. 2000).

Phytate reduction during soaking is attributed to leaching and activation of endogenous phytase enzymes. Alkaline soaking further enhances phytate dissociation by weakening mineral-phytate and protein–phytate complexes, while boiling denatures proteins and reduces available binding sites, producing

the lowest phytate levels (Jyothi et al. 1995). Tannins showed limited sensitivity to soaking alone but declined sharply during thermal treatment, likely due to increased membrane permeability and heat-induced polymerization into insoluble complexes. Saponins, which are amphiphilic glycosides located in the seed coat and cotyledon, were particularly susceptible to alkaline soaking and heat, where cell wall disruption facilitates diffusion into the soaking and cooking media (Samtiya et al. 2020).

5.1.1 | Sensory Changes and Consumer Acceptability

Texture is the most influential sensory attribute affecting consumer acceptance of processed common beans. Soaking initiates cotyledon softening, while boiling induces starch gelatinization and pectin solubilization, producing the tender texture preferred by consumers (Kwofie et al. 2020). Cooking also enhances flavour development, generating mild nutty and slightly sweet notes characteristic of well-cooked beans. Colour changes are influenced by both soaking and cooking. Soaking promotes leaching of anthocyanins in coloured varieties, while thermal processing accelerates pigment degradation and Maillard reactions, contributing to desirable aroma, colour variation and flavour complexity (Melini et al. 2023; Avendaño et al. 2024; Pirhayati et al. 2011).

5.2 | Effect of Soaking, Boiling, Fermentation and Sprouting on Nutritional and Anti-Nutritional Properties of Cowpea

Cowpea (*Vigna unguiculata*) is a staple grain legume widely cultivated across sub-Saharan Africa, valued for its drought tolerance, relatively shorter cooking time compared to common bean and high protein content. Despite these advantages, cowpea seeds contain appreciable levels of anti-nutritional factors (AFN), including phytates, tannins, trypsin inhibitors and raffinose family oligosaccharides, which limit mineral bioavailability and protein digestibility (Akinyele and Akinlosotu 1991; Samtiya et al. 2020). Traditional household processing techniques such as soaking, boiling, germination and fermentation remain practical and cost-effective strategies for mitigating these constraints.

5.2.1 | Soaking and Boiling Effects

Cowpea responds particularly well to hydration-based treatments due to its relatively permeable seed coat and lower structural rigidity compared to common bean. Table 5 summarizes the effects of soaking and boiling on the proximate composition of cowpea.

Protein content shows minimal losses during soaking but increases slightly after boiling. Similar to observations in common bean, this apparent increase is attributable to dry matter loss through leaching of soluble carbohydrates and minerals, resulting in a relative concentration effect. Thermal processing may also enhance protein digestibility by denaturing globular storage proteins and improving enzymatic accessibility. Fibre content increases after thermal treatment, likely due to starch gelatinization and partial solubilization of non-fibre components, while crude fat and ash decrease slightly as a result of leaching and thermal degradation.

Boiling significantly reduces heat-labile trypsin inhibitors, whereas fermentation provides the most comprehensive AFN reduction by combining enzymatic hydrolysis, microbial phytase activity, and organic acid production. Cowpea exhibits greater sensitivity to fermentation compared to soaking alone (Table 6). Lactic acid bacteria lower pH, thereby activating endogenous phytases and degrading oligosaccharides, which enhances mineral bioavailability and improves gastrointestinal tolerance (Adebo et al. 2020). Compared with common bean, cowpea generally requires shorter cooking times and achieves greater reductions in AFN under similar processing conditions, making it particularly suitable for low-energy household contexts.

5.2.2 | Sprouting as a Technique to Improve Protein and Mineral Bioavailability

Beyond traditional heat-based and fermentation methods, sprouting (germination) offers an accessible, low-cost approach to further enhance the nutritional and functional qualities of cowpea (*Vigna unguiculata*) (Table 7). Sprouting is influenced by variety, seed age, temperature, moisture content

TABLE 5 | Effect of soaking and boiling on proximate composition of cowpea.

Parameter (%)	Raw cowpea	Soaked (12 h, DW)	Soaked (12 h) + boiled
Moisture	10.2 ± 0.1	ND	ND
Crude protein	24.6 ± 0.2	24.9 ± 0.2	25.8 ± 0.3
Crude fibre	2.8 ± 0.1	3.0 ± 0.1	3.6 ± 0.2
Crude fat	1.6 ± 0.1	1.4 ± 0.1	1.2 ± 0.1
Ash	3.4 ± 0.1	3.2 ± 0.1	2.6 ± 0.1
Carbohydrates	57.4 ± 0.3	57.5 ± 0.4	56.8 ± 0.4

Source: Adapted from Adebiyi et al. (2017); Elhrdallous et al. (2016).

TABLE 6 | Effect of processing on anti-nutritional factors in cowpea.

AFN (mg/100 g)	Raw	Soaked (12 h)	Boiled	Fermented
Phytates	580–720	420–510	310–390	180–250
Tannins	210–340	160–220	90–130	60–90
Trypsin inhibitors (TIU/mg)	18–24	11–15	3–6	2–4
Raffinose + stachyose	High	Moderate	Low	Very low

Source: Adapted from Difo et al. (2015); Samtiya et al. (2020).

TABLE 7 | Effects of sprouting on nutritional composition of cowpea genotypes.

Parameters (per 100 g dry weight)	PL-1 (control)	PL-1 (sprouted)	PL-2 (control)	PL-2 (sprouted)
Moisture content (%)	6.91 ± 0.71	8.49 ± 0.39	6.98 ± 0.06	8.47 ± 0.51
Ash (g)	3.78 ± 0.12	3.94 ± 0.16	4.26 ± 0.22	4.50 ± 0.19
Crude protein (g)	27.15 ± 0.26	29.72 ± 0.04	30.87 ± 0.75	33.62 ± 0.56
Crude fat (g)	2.63 ± 0.27	1.99 ± 0.13	2.91 ± 0.38	2.19 ± 0.04
Crude fibre (g)	4.43 ± 0.54	6.47 ± 0.13	4.99 ± 0.19	6.51 ± 0.11
Carbohydrate (g)	66.50 ± 0.06	63.92 ± 0.19	61.92 ± 1.19	59.69 ± 0.53
Calcium (mg)	105.99 ± 1.29	116.56 ± 2.75	109.65 ± 2.84	116.17 ± 2.75
Iron (mg)	5.91 ± 0.14	5.99 ± 0.01	6.75 ± 0.18	6.78 ± 0.06
Vitamin C (mg)	0.08 ± 0.14	3.03 ± 0.31	0.19 ± 0.33	1.79 ± 0.63
Phytic acid (mg)	308.83 ± 5.21	19.07 ± 3.06	380.34 ± 3.01	45.54 ± 3.06
Trypsin inhibitor activity (TIA)	5.46 ± 1.93	4.05 ± 0.17	6.03 ± 0.01	3.32 ± 0.50
In vitro protein digestibility (IVPD, %)	59.76 ± 1.93	64.99 ± 1.97	63.83 ± 2.44	71.66 ± 3.65

Abbreviations: PL-1: Pant Lobia; PL-2: Pant Lobia-2 (improved cowpea varieties).

Source: Adapted from Devi et al. (2015).

TABLE 8a | Proximate composition of lablab before and after processing.

Parameter (%)	Raw lablab	Soaked (12 h)	Boiled	Fermented
Crude protein	22.8 ± 0.3	23.2 ± 0.3	24.5 ± 0.4	25.6 ± 0.4
Crude fibre	4.1 ± 0.2	4.3 ± 0.2	4.9 ± 0.3	5.1 ± 0.3
Crude fat	1.3 ± 0.1	1.2 ± 0.1	1.1 ± 0.1	1.0 ± 0.1
Ash	3.8 ± 0.1	3.6 ± 0.1	3.1 ± 0.1	2.9 ± 0.1

Source: Adapted from Adegunwa et al. (2014).

and exposure to light or darkness. Optimal soaking before sprouting ranges from 3 to 12 h, depending on the genotype, while the preferred sprouting temperature is around 25°C for 24 h. Temperatures above 28°C may lead to off-flavours and sliminess, while extended sprouting beyond 48–72 h can result in undesirable odours and discoloration (Olapade et al. 2002; Devi et al. 2015).

Sprouting led to a significant increase in moisture content due to water uptake during soaking, while ash content increased as a result of starch consumption and reduced dry matter, concentrating minerals (Lorenzo et al. 1980). Crude protein content increased substantially, reflecting the relative loss of carbohydrates through respiration and the metabolic reorganization of seed proteins (Uppal and Bains 2012). Conversely, crude fat decreased due to oxidation and utilization of fatty acids during germination (Kwon 1994). Carbohydrates declined as starch reserves were mobilized for embryonic growth, while β-amylase activity hydrolysed starch into simpler sugars, providing energy for cell division (Vidal-Valverde et al. 2002). Mineral content,

TABLE 8b | Effect of processing on anti-nutritional factors in lablab.

ANF	Raw	Soaked	Boiled	Fermented
Phytates (mg/100 g)	850–1100	620–780	410–520	200–310
Tannins (mg/100 g)	380–520	260–340	120–180	70–110
Trypsin inhibitors (TIU/mg)	26–34	18–22	4–7	2–3
Oxalates (mg/100 g)	120–180	90–130	60–90	40–60

Source: Adapted from Vadivel and Pugalenthi (2010); Samtiya et al. (2020).

particularly calcium, increased due to both concentration effects and the presence of mineral salts in sprouting water (Dave and Shah 2008;). Vitamin C synthesis was reactivated during germination, enhancing antioxidant capacity (Bibi et al. 2008; Mao et al. 2005).

Anti-nutritional factors (ANFs), including phytic acid and trypsin inhibitors, were markedly reduced due to enzymatic hydrolysis and leaching during soaking, while in vitro protein digestibility increased, reflecting improved bioavailability of proteins (Uppal and Bains 2012; Shah et al. 2011; Sinha et al. 2005). Overall, sprouting significantly enhances the nutritional profile of cowpea by increasing protein, mineral and vitamin content, reducing ANFs, and improving protein digestibility, all without the need for heat-based processing. This makes sprouting a particularly valuable approach for low-resource households seeking to preserve heat-sensitive nutrients while improving dietary quality.

5.3 | Effect of Processing on Nutritional and Anti-Nutritional Properties of Lablab (*Lablab purpureus*)

Lablab (*Lablab purpureus*) is an underutilized multipurpose legume cultivated for grain, vegetable pods, fodder and soil fertility improvement. Despite its agronomic resilience and high protein content, lablab remains under-represented in food processing literature due to concerns related to seed hardness, prolonged cooking time and elevated levels of ANFs such as phytates, tannins and enzyme inhibitors (Akinyele 1991; Kay 1979). Recent studies demonstrate that lablab responds well to combined traditional and modern processing methods, positioning it as a strong candidate for climate-resilient nutrition systems (Tables 8a and 8b).

5.4 | Comparative Synthesis Across Common Bean, Cowpea and Lablab

Across the three legumes, distinct species-specific responses to processing are evident (Table 9). Common bean (*Phaseolus vulgaris*) generally requires intensive thermal treatments, such as boiling and alkaline soaking, to achieve substantial reductions in

TABLE 9 | Summary of major anti-nutritional factors (ANFs) and their most effective mitigation strategies in common bean, cowpea and lablab.

Anti-nutritional factor	Common bean (*Phaseolus vulgaris*)	Cowpea (*Vigna unguiculata*)	Lablab (*Lablab purpureus*)	Primary mechanism of reduction
Phytates	Soaking + boiling in alkaline solution (Na_2CO_3); controlled fermentation	Fermentation > boiling > soaking	Fermentation + boiling	Leaching, phytase activation, microbial hydrolysis
Condensed tannins	Boiling; dehulling	Boiling; fermentation	Fermentation > boiling	Thermal degradation, complexation, microbial breakdown
Trypsin and protease inhibitors	Boiling; extrusion	Boiling; fermentation	Boiling; extrusion	Heat denaturation, shear-induced inactivation
Lectins (haemagglutinins)	Thorough boiling (> 95°C)	Boiling	Boiling	Heat-labile protein denaturation
Raffinose and stachyose (oligosaccharides)	Soaking + boiling in alkaline medium	Fermentation > boiling	Fermentation	Enzymatic hydrolysis by α-galactosidase
Saponins	Alkaline soaking + boiling	Boiling; fermentation	Soaking + fermentation	Solubilization, membrane disruption
Oxalates	Soaking + boiling	Boiling	Boiling; fermentation	Leaching, thermal decomposition

key anti-nutritional factors. Although these methods effectively lower phytates, tannins and protease inhibitors, they often involve longer cooking times and higher energy inputs to enhance nutrient bioavailability (Samtiya et al. 2020; Misgana and Bajo 2020). In contrast, cowpea (*Vigna unguiculata*) tends to hydrate and respond more readily to mild processing, with fermentation and conventional boiling significantly reducing enzyme inhibitors and oligosaccharides at relatively lower inputs, largely due to microbial action and enzymatic degradation during fermentation that improves digestibility (Adebo et al. 2022; Abdulmajid Haji 2021).

Although *Lablab purpureus* often contains comparatively high levels of phytates, tannins and protease inhibitors in its raw state, integrated processing strategies especially when combining soaking, boiling and fermentation produce marked reductions in these compounds, thereby improving nutrient accessibility (Samtiya et al. 2020; Kalpanadevi and Mohan 2013). From a nutritional systems perspective: Cowpea represents a more energy-efficient processing pathway, achieving meaningful decreases in major ANFs under milder conditions. *Phaseolus vulgaris* offers flexibility across diverse culinary practices but requires more rigorous treatment. *Lablab purpureus* delivers some of the highest transformation gains when appropriately processed. These complementary attributes underscore the need for species-specific processing recommendations rather than generalized legume guidelines, particularly in household and semi-industrial food preparation contexts. Including lablab in this comparative framework helps address a critical literature gap and aligns with emerging priorities in promoting climate-resilient, underutilized crops and sustainable protein diversification (Samtiya et al. 2020; Adebo et al. 2022).

6 | Processing-ANF Reduction, Bioavailability and Adoption Pathway

Processing of legumes such as *Phaseolus vulgaris*, *Vigna unguiculata* and *Lablab purpureus* is central to unlocking their nutritional potential. Traditional techniques including soaking, boiling, germination and spontaneous fermentation act by leaching water-soluble ANFs, denaturing enzyme inhibitors and activating endogenous enzymes such as phytase to release bound minerals (Kumari and Roy 2023; Samtiya et al. 2020). Modern interventions, including controlled fermentation, extrusion and chemical modification, further enhance these effects by applying regulated temperature, pressure and microbial activity to achieve predictable ANF reduction while improving functional and sensory properties (Chavez-Lopez et al. 2014). These processing steps directly reduce ANF concentrations, thereby improving nutrient bioavailability (iron, zinc, calcium) and protein digestibility. At the same time, sensory characteristics such as texture, flavour and colour improve, while cooking time decreases, enhancing consumer acceptance and likelihood of dietary adoption. Processing–ANF reduction–bioavailability–adoption pathway illustrates how traditional and modern legume processing strategies enhance nutrient utilization, sensory quality and dietary integration across common bean, cowpea and lablab (Figure 1).

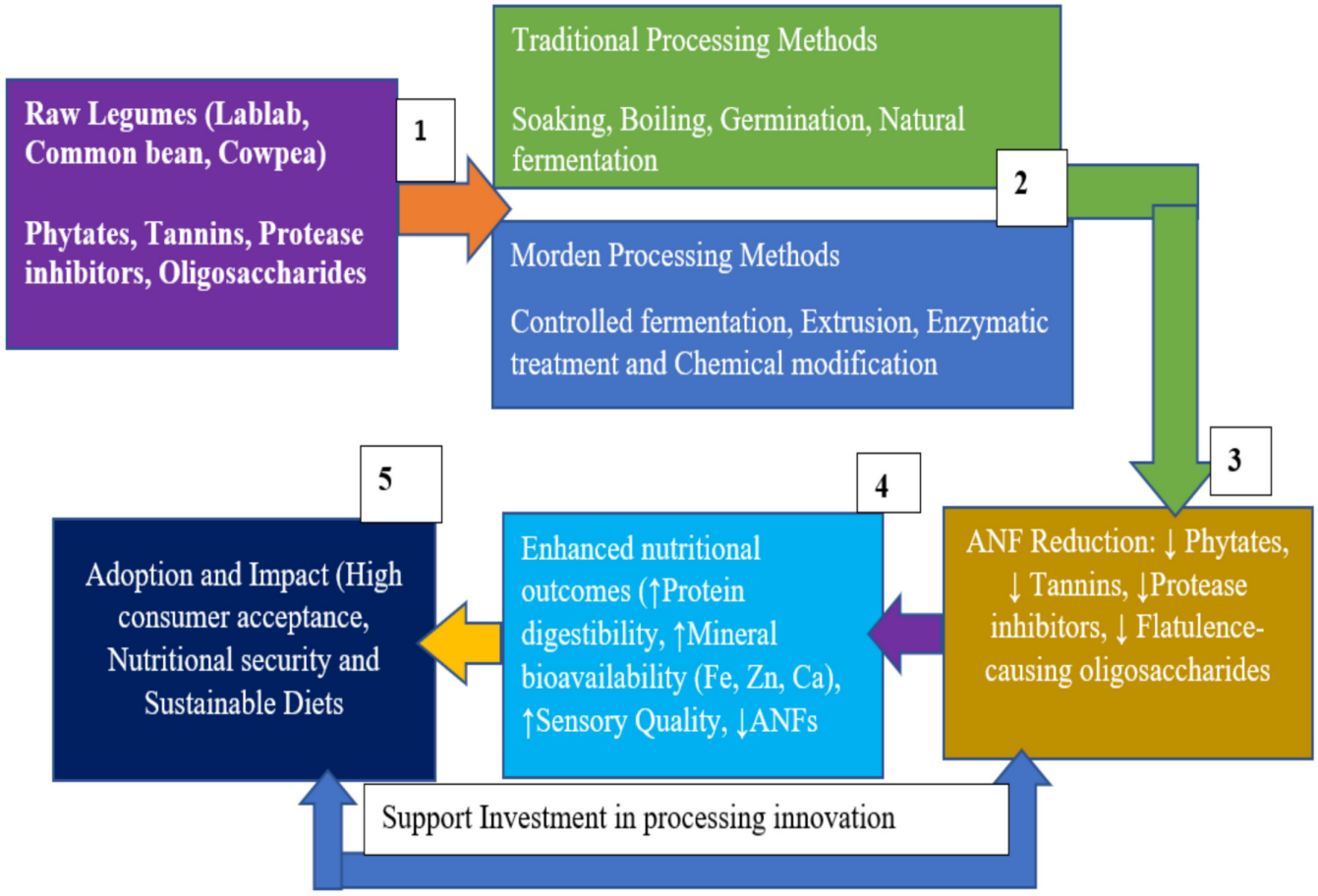


FIGURE 1 | Processing–ANF reduction–bioavailability–adoption pathway illustrating how traditional and modern legume processing strategies enhance nutrient utilization, sensory quality and dietary integration of common bean, cowpea and lablab.

7 | Optimization of Processing Techniques—Food Quality and Safety

Optimizing legume processing is essential to balance ANF reduction with nutrient retention and sensory quality. Integrated and sequential methods such as soaking 8–12 h followed by boiling, steaming, fermentation or sprouting maximize nutrient retention and ANF reduction (Qureshi et al. 2020; Kinyanjui et al. 2015). Excessive sprouting or high temperatures can lead to off-flavours, microbial contamination or nutrient degradation. Tailored strategies based on legume species, intended use and household capacity provide the most effective and practical outcomes, particularly for smallholder contexts.

8 | Policy and Research Gaps in Mitigating ANFs in Legumes

8.1 | Policy Gaps

National food and nutrition policies in many low- and middle-income countries often omit crop-specific processing recommendations. This limits the translation of scientific knowledge on anti-nutritional factor (ANF) mitigation into practical household and institutional practices. Extension services frequently promote generic legume cooking methods, failing to account for species-specific responses. As highlighted in this review, *Phaseolus vulgaris*, *Vigna unguiculata* and *Lablab purpureus* respond differently to soaking, boiling and fermentation, underscoring the importance of tailored guidance. Underutilized legumes such as *Lablab purpureus* remain largely excluded from school feeding programs, public procurement frameworks and value-chain initiatives. This marginalization constrains diversification of protein sources and limits opportunities for these resilient legumes to contribute to sustainable diets and nutrition-sensitive food systems.

8.2 | Research Gaps

From a research perspective, comparative processing studies across multiple legumes remain limited, with most investigations focusing on single species under controlled conditions. Data on *Lablab purpureus* processing are fragmented and often lack standardized protocols, making cross-study comparisons and generalized recommendations challenging. Emerging technologies, including controlled fermentation and extrusion, are rarely evaluated in African contexts, particularly in terms of affordability, scalability and consumer acceptance. Furthermore, in vivo bioavailability and human absorption studies following processing remain scarce, leaving a critical gap in understanding the actual nutritional benefits of ANF reduction in real diets. Addressing these gaps requires interdisciplinary approaches linking food science, nutrition, agronomy, policy and behavioural research.

9 | Conclusion and Future Perspectives

This review synthesizes anti-nutritional factors (ANFs) and mitigation strategies in *Lablab purpureus*, common bean (*Phaseolus vulgaris*) and cowpea (*Vigna unguiculata*), highlighting both shared patterns and species-specific responses to processing. Traditional household practices such as soaking, boiling, fermentation and germination consistently reduce major ANFs, while modern approaches, including controlled fermentation and extrusion, offer greater precision and efficiency. *Lablab purpureus* demonstrates high responsiveness to processing but remains underrepresented in research. Comparative synthesis shows that cowpea generally requires milder processing, common bean provides flexibility across diverse culinary practices and lablab achieves substantial nutrient gains when appropriately processed. Integrated processing strategies enhance digestibility, nutrient bioavailability and sensory qualities, supporting adoption in household and semi-industrial contexts. Future research should prioritize standardized, comparative processing studies across multiple legumes, in vivo bioavailability and human absorption assessments and expanded investigation of lablab under household, community and industrial conditions. From a policy perspective, integrating legume-specific processing recommendations into national nutrition strategies, extension programs and institutional feeding schemes could significantly enhance the nutritional impact of legumes, thereby promoting resilient, sustainable and nutrition-sensitive food systems.

Author Contributions

Leonard R. Ndibalema: conceptualization (lead), data curation (lead), writing – original draft (lead), writing – review and editing (equal). **Edmond Alavaisha:** data curation (supporting), writing – original draft (supporting), writing – review and editing (equal). **Joseph Kalonga:** data curation (supporting), writing – original draft (supporting), writing – review and editing (equal). **Mkabwa L. K. Manoko:** conceptualization (supporting), writing – original draft (supporting), supervision (supporting), writing – review and editing (equal). **Charles O. Joseph:** data curation (supporting), writing – original draft (supporting), supervision (lead), validation (lead), writing – review and editing (equal).

Ethics Statement

This review article did not involve human or animal subjects. Ethical approval was therefore not required. All sources have been appropriately cited, and the manuscript adheres to ethical standards for academic integrity and responsible reporting of previously published research.

Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

This review article did not generate new experimental data. All data summarized are from published studies, which are cited in the manuscript and listed in the reference section. Any additional materials or compiled tables can be shared upon reasonable request from the corresponding author.

References

Abdulmajid Haji, A. 2021. "Effect of Fermentation on Antinutritional Factors in Cowpea." *Journal of Food Processing and Preservation* 45, no. 6: e15527.

Abulkalam, A. Z. 2002. "Anti-Nutritional Factors in Plant Foods and Their Effects on Human Health." *Food Reviews International* 18, no. 4: 271–290.

Adamcova, D., L. Sobotka, and R. Konecny. 2021. "Lectins in Legumes: Occurrence, Toxicity, and Processing Mitigation." *Food Chemistry* 340: 127927.

Adebayo, A., J. Adegbite, and O. Olaniran. 2014. "Influence of Soaking and Cooking on the Anti-Nutritional Factors in Cowpea." *Journal of Food Science and Technology* 51, no. 12: 3829–3836.

Adegunwa, M. O., E. O. Alamu, and L. A. Omitogun. 2014. "Effect of Processing on the Nutritional Content of Lablab Bean Flour." *Journal of Food Processing and Preservation* 38, no. 2: 489–495.

Adebiyi, A. P., O. O. Olapade, and O. T. Ojo. 2017. "Nutritional Changes in Cowpea During Processing: Soaking and Boiling Effects." *African Journal of Food Science* 11, no. 2: 32–40.

Adebo, O. A., E. Kayitesi, and P. B. Njobeh. 2020. "Fermentation as a Tool to Reduce Anti-Nutritional Factors in Legumes." *Food Reviews International* 36, no. 4: 340–358.

Adebo, O. A., O. O. Oladele, and E. Kayitesi. 2022. "Traditional and Modern Processing Strategies to Mitigate Anti-Nutritional Factors in Legumes." *Frontiers in Nutrition* 9: 987654.

Akinyele, I. O. 1991. "Nutritional Evaluation of African Yam Bean and Other Tropical Legumes." *Journal of Food Science* 56, no. 4: 1056–1060.

Akinyele, I. O., and T. A. Akinlosotu. 1991. "Nutritional Evaluation and Processing of Cowpea and Lablab." *Tropical Science* 31, no. 4: 271–280.

Avendaño, A., M. Fernández, and V. Melini. 2024. "Effect of Thermal Processing on Sensory and Bioactive Compounds in Legumes." *Journal of Food Quality* 2024: 987321.

Barakat, H., H. El-Mansy, and M. Ahmed. 2023. "Advances in Processing Technologies for the Metabolism of Amylase Inhibitors in Beans." *Gastroenterology* 94, no. 2: 387–392.

Benzaghta, M., J. Smith, and P. Ochieng. 2021. "Sustainable Utilization of Underutilized Legumes: Opportunities and Challenges for African Smallholder Farmers." *Journal of Agricultural Development* 12, no. 3: 45–61.

Bibi, N., S. Khalid, and S. Hussain. 2008. "Vitamin C Synthesis During Germination of Legumes." *Pakistan Journal of Nutrition* 7, no. 6: 792–796.

Bouzier, C., J. M. Lecerf, and C. Leelereq. 2023. "Bioactive Compounds and Antinutritional Factors in Legumes: Nutritional Implications and Processing Strategies." *Foods* 12, no. 7: 1502.

Bramer, W. M., M. L. Rethlefsen, J. Kleijnen, and O. H. Franco. 2017. "Optimal Database Combinations for Literature Searches in Systematic Reviews: A Prospective Exploratory Study." *Systematic Reviews* 6, no. 1: 245. https://doi.org/10.1186/s13643-017-0624-7.

Broughton, W. J., G. Hernández, M. Blair, S. Beebe, P. Gepts, and J. Vanderleyden. 2003. "Beans (Phaseolus spp.)—Model Food Legumes." *Plant and Soil* 252, no. 1: 55–128.

Campos-Vega, R., B. D. Oomah, G. Loarca-Piña, and H. Vergara-Castañeda. 2010. "Nutritional Composition and Bioactive Components of Legume Seeds." *Food Research International* 43, no. 2: 461–472.

Chavez-Lopez, M. A., B. Ramirez-Wong, and A. Gonzalez. 2014. "Modern Processing of Legumes to Reduce Anti-Nutritional Factors." *Journal of Food Engineering* 132: 75–84.

Dave, R., and N. P. Shah. 2008. "Effects of Germination on Nutritional and Functional Properties of Legumes." *Food Chemistry* 109, no. 3: 699–705.

Devi, C. B., A. Kushwah, and A. Kumar. 2015. "Sprouting Characteristics and Nutritional Composition of Cowpea Varieties." *Legume Research* 38, no. 4: 530–536.

Difo, H. V., E. Onyike, and L. Eboh. 2015. "Effects of Fermentation on Anti-Nutritional Factors in Cowpea." *African Journal of Food Science* 9, no. 9: 503–509.

Duenas, M., T. Hernandez, I. Estrella, and D. Fernandez. 2002. "Distribution of Polyphenols and Phytates in Legume Seeds." *Journal of Agricultural and Food Chemistry* 50, no. 6: 1916–1920.

Elhrdallous, S. B., I. I. Khalid, A. A. Gobouri, and S. H. Abdel-Hafez. 2016. "Effects of Soaking and Cooking on Nutritional Quality of Cowpea." *Food Science and Nutrition* 4, no. 2: 256–263.

FAO. 2022. *The State of Food Security and Nutrition in the World 2022: Building Resilience for Food Security and Nutrition*. Food and Agriculture Organization of the United Nations.

Gemede, H. F., N. Ratta, and G. D. Haki. 2014. "Anti-Nutritional Factors in Legumes and Their Reduction Methods." *Journal of Nutrition & Food Sciences* 4, no. 2: 1–7.

Gilani, G. S., X. Wu, and K. A. Cockell. 2012. "Impact of Anti-Nutritional Factors in Legumes on Protein and Mineral Bioavailability." *Critical Reviews in Food Science and Nutrition* 52, no. 11: 930–948.

Guce, A., M. Fuchs, and H. Becker. 2009. "Lectins, Trypsin Inhibitors and Phytates in Legumes: Nutritional Implications." *Food Chemistry* 114, no. 4: 1233–1240.

Gupta, R., S. Gangoliya, and N. Singh. 2013. "Reduction of Phytic Acid and Improvement of Mineral Bioavailability in Legumes." *Journal of Food Science and Technology* 50, no. 6: 1110–1121.

Han, J., and B. Baik. 2006. "Reduction of Oligosaccharides in Common Beans by Soaking and Cooking." *Journal of Food Science* 71, no. 7: S513–S519.

Jepleting, J., C. Mutingi, and C. Onyango. 2025. "Influence of Soaking and Alkaline Treatment on Raffinose Family Oligosaccharides and Anti-Nutritional Factors in Common Beans." *Journal of Food Processing and Preservation* 49, no. 1: e17845.

Jyothi, N., S. Sathe, and D. Salunkhe. 1995. "Effect of Processing on Phytate Content of Legumes." *Journal of Food Science* 60, no. 4: 807–811.

Kalpanadevi, V., and S. Mohan. 2013. "Effect of Traditional Processing on Nutritional and Anti-Nutritional Properties of Underutilized Legumes." *Journal of Food Science and Technology* 50, no. 6: 1191–1197.

Kaur, S., S. Singh, and R. Chawla. 2015. "Extrusion Cooking of Legumes: Reduction of Anti-Nutritional Factors." *Food Science and Technology International* 21, no. 3: 185–195.

Kay, D. E. 1979. *Tropical Legumes: Resources for Food and Forage*. Academic Press.

Kinyanjui, N., R. Muriuki, and P. Gichuhi. 2015. "Impact of Boiling on Anti-Nutritional Factors in Legumes." *African Journal of Food Science* 9, no. 9: 453–460.

Kumar, S., B. Singh, and P. Sharma. 2021. "Secondary Metabolites and Anti-Nutritional Factors in Legumes: Biological Roles and Implications for Human Nutrition." *Journal of Food Science and Nutrition* 9, no. 7: 3562–3573.

Kumari, S., and D. Roy. 2023. "Nutritional Significance and Reduction of Anti-Nutrition Factors in Legumes Through Processing: A Review." *Food Research International* 165: 112456.

Kwofie, E. M., I. Oduro, W. O. Ellis, and C. Tortoe. 2020. "Effect of Soaking and Cooking on the Texture, Sensory Properties, and Nutritional Quality of Common Beans (Phaseolus vulgaris L.)." *Journal of Food Science and Technology* 57, no. 6: 2156–2164.

Kwon, T. W. 1994. "Changes in Lipids During Germination of Legumes." *Journal of Food Science* 59, no. 3: 588–592.

Kyriazakis, I., and C. T. Whitemore. 2006. *Whittemore's Science and Practice of Pig Production*. 3rd ed. Blackwell Publishing.

Leech, J. 2019. "Lectins: Their Role in Nutrition and Human Health." *Journal of Nutrition and Food Science* 9, no. 3: 1–6.

Lorenzo, R., E. Arendt, and M. Mehta. 1980. "Mineral Retention During Sprouting of Legumes." *Journal of Agricultural and Food Chemistry* 28, no. 6: 1236–1240.

Mao, X., F. Liu, and R. Yang. 2005. "Vitamin C Synthesis in Germinating Legumes." *Food Chemistry* 92, no. 4: 691–696.

Melini, V., A. Avendaño, and M. Gomez. 2023. "Thermal Processing Effects on Colour, Flavour, and Bioactive Compounds of Legumes." *Critical Reviews in Food Science and Nutrition* 63, no. 4: 1205–1225.

Misgana, T., and F. Bajo. 2020. "Mitigation of Anti-Nutritional Factors in Common Beans Through Traditional Processing." *Food Science & Nutrition* 8, no. 6: 2874–2885.

Oboh, G., H. Raddatz, and T. Henle. 2000. "Reduction of Flatulence-Causing Oligosaccharides in Beans." *Food Chemistry* 70, no. 2: 195–199.

Olapade, O., L. Sanni, and J. Fashakin. 2002. "Cowpea Germination: Effects on Nutrition and Anti-Nutritional Factors." *Journal of Food Processing and Preservation* 26, no. 5: 331–342.

Paez, A. 2017. "Grey Literature: An Important Resource in Systematic Reviews." *Journal of Evidence-Based Medicine* 10, no. 3: 233–240. https://doi.org/10.1111/jebm.12266.

Pirhayati, M., S. Goli, and R. Khaksar. 2011. "Effect of Thermal Processing on Colour, Flavour, and Anti-Nutritional Factors in Legumes." *Journal of Food Processing and Preservation* 35, no. 5: 635–645.

Qureshi, T., M. Farooq, and A. Khan. 2020. "Effect of Soaking and Boiling on Nutritional Composition and Anti-Nutritional Factors in Common Beans." *Journal of Food Science and Technology* 57, no. 11: 4027–4036.

Reddy, N., M. Pierson, and S. Sathe. 1985. "Distribution of Tannins and Phytates in Legume Seeds." *Journal of Food Science* 50, no. 6: 1747–1749.

Samtiya, M., R. E. Aluko, and T. Dhewa. 2020. "Plant Food Anti-Nutritional Factors and Their Reduction Strategies: An Overview." *Food Production, Processing, and Antinutrition* 2: 6.

Savage, G. P., J. Lee, and S. Deo. 2003. "The Nutritional Value of Peas and Beans in Human Diets." *Nutritional Research Review* 16, no. 2: 193–206.

Shah, S., A. Zeb, T. Masood, et al. 2011. "Effects of Sprouting Time on Biochemical and Nutritional Qualities of Mungbean Varieties." *African Journal of Agricultural Research* 6, no. 22: 5091–5098.

Siddhuraju, P., K. Becker, and H. Makkar. 2001. "Effect of Soaking on Anti-Nutritional Factors in Legumes." *Journal of the Science of Food and Agriculture* 81, no. 5: 476–483.

Siener, R., R. Honow, and A. Hesse. 2021. "Oxalate Content of Plant Food and Its Dietary Implications for Kidney Stone Formation." *Urological Research Ach* 49, no. 1: 19–25.

Sinha, R., S. Aggarwal, and B. Singh. 2005. "Sprouting-Induced Reduction of Anti-Nutritional Factors in Legumes." *Food Chemistry* 93, no. 4: 561–567.

Snyder, H. 2019. "Literature Review as a Research Methodology: An Overview and Guidelines." *Journal of Business Research* 104: 333–339. https://doi.org/10.1016/j.jbusres.2019.07.039.

Soetan, K. O., and O. E. Oyewole. 2009. "The Need for Adequate Processing to Reduce the Antinutritional Factors in Plants Used as Human Foods and Animal Feeds." *African Journal of Food Science* 3, no. 9: 223–232.

Torraco, R. J. 2016. "Writing Integrative Literature Reviews: Guidelines and Examples." *Human Resource Development Review* 15, no. 4: 404–428. https://doi.org/10.1177/1534484316671606.

Uppal, V., and K. Bains. 2012. "Effects of Germination on Protein Digestibility and Antinutritional Factors of Legumes." *Journal of Food Science and Technology* 49, no. 3: 351–357.

USDA. 2025. *Dietary Guidelines for Americans 2025-2030*. United States Department of Agriculture and U.S. Department of Health and Human Services.

Vadivel, V., and M. Pugalenthi. 2010. "Nutritional Evaluation of Lablab Bean and the Effect of Processing on Antinutritional Factors." *Food Chemistry* 199, no. 2: 657–662.

Vidal-Valverde, C., J. Frias, and S. Valverde. 2002. "Changes in Oligosaccharides and Protein Digestibility During Sprouting of Legumes." *Journal of Food Composition and Analysis* 15, no. 6: 617–627.

Wang, N., G. Ryu, and B. Baik. 2008. "Effect of Soaking and Cooking on Protein Digestibility of Common Beans." *Journal of Food Science* 73, no. 7: C510–C514.

Whittemore, R., and K. Knafl. 2005. "The Integrative Review: Updated Methodology." *Journal of Advanced Nursing* 52, no. 5: 546–553. https://doi.org/10.1111/j.1365-2648.2005.03621.x.

Yi, J., L. Zhao, and Y. Zhang. 2021. "Integration of Traditional and Modern Processing Strategies for Legumes." *Food Chemistry* 348: 129046.