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Review article

NUTRITIONAL COMPOSITION, ANTINUTRITIONAL FACTORS, PROCESSING METHODS AND APPLICATIONS OF WINGED BEAN (*PSOPHOCARPUS TETRAGONOLOBUS*): A REVIEW

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ABSTRACT

Winged bean (*Psophocarpus tetragonolobus*) seeds contain significant nutritional profile with high protein (29.8-40.7%), essential amino acids, dietary fiber, beneficial unsaturated fats, and micronutrients. Comparative analysis indicates that WB seeds are equal or surpass soybean and chickpea in terms of protein, iron, and zinc content. WB also contain diverse bioactive peptides and antioxidant phenolics. However, their adoption is affected by hardseededness and elevated antinutritional factors i.e., trypsin inhibitors, tannins, and phytates. These compounds restrict nutrient absorption and digestibility. This review evaluates these challenges and highlights conventional processing (dehulling, soaking, boiling, fermentation) and suggests emerging processing technologies for improving nutritional quality and functionality. Recent findings are included regarding safety and allergenicity. Presence of allergenic proteins were noticed and suggested the need for population-specific screening. Nutritional studies and limited clinical trials suggest WB products support positive health outcomes when properly processed. The manuscript identifies critical opportunities and research gaps to inform further innovation and promote the broader use of WB seeds as a sustainable functional food ingredient.

1. Introduction

According to WHO (WHO, 2024), 390 million individuals were underweight in 2022, while 2.5 billion population was overweight, with 890 million of these people were having obesity. There were 13.7 million children severely malnutrition and 22.3% of these children were under five years age (WHO, 2023). Winged Bean (*Psophocarpus tetragonolobus*) is a high in nutrients legume with huge potential for addressing malnutrition challenges globally. Raw WB leaves contain 74 calories, 5.9 g of protein, 14 g of carbohydrates, and 1.1 g of fat/100g. The tubers contain 148 calories/100g, with a macronutrient composition of 5% fat, 67% carbohydrates, and 28% protein (Adegboyega *et al.,* 2020). WB is known as a "super crop"

and is an essential legume for world food security. It is native to the humid tropics (India, Sri Lanka, Malaysia, Thailand, Vietnam, Burma, Indonesia, New Guinea, Philippines, Ghana, and Nigeria) and has gained recognition due to its significant nutritional value and ability to grow in a diverse climatic condition. The need to identify wholesome and sustainable food sources increases with increase in global population. WB seeds are high in protein content and adaptability, which has great potential as an important crop for preventing malnutrition and ensuring food security in developing countries.

WB is recognized as a "soybean of the tropics" for its ability to deliver high-protein yields under hot, humid, and low-input farming systems (Adebayo & Shonde, 2024; Tanzi *et al.,* 2019). In tropical regions soybean cultivation depends on higher external nitrogen inputs. On the other hand, WB forms strong symbiotic nitrogen-fixing associations with a broad range of rhizobial bacteria (Ayilara *et al.,* 2022; Bassal *et al.,* 2020). This property of WB assists in productive cultivation with minimal synthetic fertilizer. This reduction in fertilizer demand can significantly lower nitrous oxide emissions, while improving soil fertility and microbial health (Vatanparast *et al.,* 2016). Perennial or tuber-producing growth habit and whole-plant edibility (pods, seeds, leaves, flowers, tubers) make WB significantly resource-efficient. The ability of WB to grow on humid, low-fertility soils and marginal lands expands the possibilities for climate-resilient diversification and supports local protein self-sufficiency (Mahobia *et al.,* 2024; Mohanty *et al.,* 2020). Nutritional analyses show seed protein content and amino acid profiles comparable to soybean. Major advantage of WB compared to soybean is in adaptability to tropical rainfall and heat stress. This can lower dependence on long-distance protein imports and reduce transport-related emissions (Thrane *et al.,* 2024). Studies have demonstrated substantial nodulation and nitrogen accumulation across WB accessions. highlighting opportunities for breeding climate-smart varieties that further enhance soil health and minimize inputs https://www.cabidigitallibrary.org/doi/pdf/10.1079/9781800624658.0013?download=true(Mahobia *et al.,* 2024). Field studies in Myanmar shown that targeted management *i.e.,* trellis support, can improve seed and tuber productivity. This can further increase versatility to the WB application in food systems (Maw *et al.,* 2023). Life cycle assessments (LCAs) for soybean are well-established and clearly identify environmental hotspots *i.e.,* particularly from fertilizer use and land-use change (NOPA, 2024). There is still lack of dedicated, comprehensive LCA for WB. Given its low fertilizer footprint, adaptability to marginal lands, and contribution to agroecosystem resilience, there is a strong case for quantifying its comparative climate benefits in tropical production systems (Kumar *et al.,* 2019; Mohanty *et al.,* 2020; Tsoutsoura, 2025).

One of the most observed characteristics of WB is their total edibility. The entire plant including seeds, leaves, pods, and tubers is edible and nutritious, and it is a 100% sustainable food crop as shown in Figure 1. The seeds have special importance for their protein content, which is comparable to soybean, while the leaves and young pods are used as nutritious vegetables. The underutilized tubers are high in carbohydrates and can be used as an energy source. This "whole plant utilization" differentiates WB from other crops and shows its capacity to contribute to a circular and waste-free food chain. It contains high-quality protein, vital amino acids, dietary fiber, vitamins, and minerals. It also contains bioactive compounds like antioxidants and polyphenols with number of health benefits. Like most legumes, WB seeds also contain antinutritional compounds *i.e.,* trypsin inhibitors, tannins, and phytic acid, which reduces nutrient absorption and limits its utilization. All of these challenges may be addressed with the use of suitable food processing methods that prevent antinutritional factors while preserving or enhancing nutritional potential.

The processing and utilization of WB seeds remained unexplored compared to other

legumes like soybean. New processing technologies *i.e.,* thermal processing, fermentation, pulsed electric field, cold plasma, and enzymatic hydrolysis can help the industry achieve full potential of this super crop. The purpose of this article is to present a wide overview of the nutritional properties, processing, and application of WB seeds with its potential in addressing global nutrition problems and building sustainable food systems.

Recent research highlights the global importance of exploring underutilized legumes such as WB for improved food diversity and nutritional security. This is important in tropical regions with protein deficiency and soil degradation (Tanzi *et al.,* 2019).

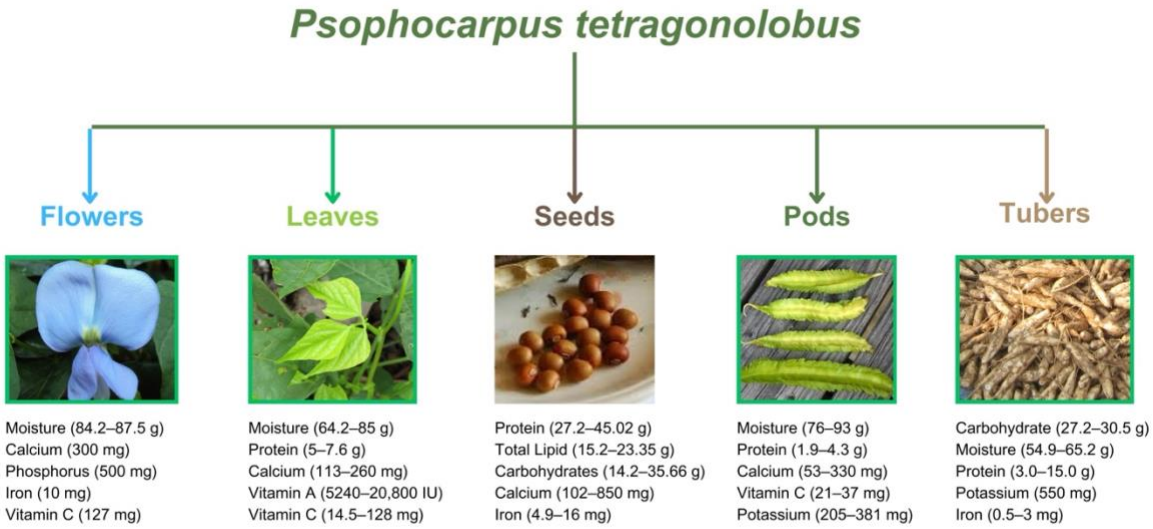

Figure 1. Major nutrients in different parts of WB (*Psophocarpus tetragonolobus)* (Bepary et al., 2023; Starr, 2011; STRONGlk7, 2012; Vinayaraj, 2013; Wagaung, 2008).

While all plant parts of WB are edible and valuable, this review emphasizes the mature seed due to its high nutrition value, processing challenges, and potential as a sustainable alternative to staple legumes. Notably, the underutilization of seed is mainly contributed to its hardness and high levels of anti-nutritional factors. This necessitates targeted processing solutions (Han *et al.,* 2022).

2. Nutritional composition of winged bean

WB seeds are an excellent source of plant-based protein (**Table 1**). They are also high in dietary fiber, vitamins, and minerals such as iron, calcium, and phosphorous. Furthermore, WB seeds contain healthy fats, specifically polyunsaturated fatty acids, and are low in calories. This makes them a valuable dietary source for preventing malnutrition and maintaining general health. Their unique composition serves as a feasible crop for long-term nutrition in tropical and subtropical conditions.

2.1. Protein content and amino acids of winged bean seeds

WB seeds are valuable source of nutrition due to its high protein content and excellent amino acid composition as shown in Figure 2. The seeds are highly rich in proteins, containing around 34.3% to 40.7% protein in dry weight (Ho *et al.,* 2024; Omprakash *et al.,* 2018). Prakash *et al.* (1987) stated that protein content of WB seeds varied depending cultivar and growth conditions. The amino acid profile of the WB seeds (Table 2) indicated its nutritional diversity and importance as a high-quality plant protein source.

Table 1. Physicochemical properties of winged bean

Component (%)	WB Seeds (Mature Dried)	WB Mature Pods	WB Mature Leaves	Soybean	Chickpea
Moisture	7.36–12.58	87.2–90.0	64.20-85.0	6.98-8.58	7.80–9.50
Protein	29.80–40.70	2.10–3.80	1.90–7.50	36.50–43.70	17.40–20.70
Fat	15.80–21.30	0.24–3.40	0.60–1.40	14.00-21.32	3.30-4.10
Carbohydrates	19.93–33.69	1.10–6.80	3.10–8.50	29.8-32.75	50.10–61.10
Crude Fibre	4.75–15.73	1.00–2.90	1.70–4.20	5.10–5.90	10.20–17.40
Ash	3.52–4.90	0.62–1.90	1.10–2.90	4.80–5.62	3.20-3.50

Table 2. Amino acid profile comparison of dried winged bean and soybeans

Amino Acid (mg/100g of protein)	WB Seeds (Mature Dried)	WB Pods	WB Leaves	Soybean	Chickpea
Alanine	6.20-8.30	3.71-4.40	4.16-6.40	4.30-4.50	4.20-4.40
Arginine	4.00-6.20	4.75-6.20	2.30-4.11	7.20-7.50	8.30-8.80
Aspartic Acid	7.50-12.30	9.13-11.30	8.59-10.40	11.70-11.90	11.20-11.80
Cysteine	0.40-1.70	0.90-2.06	0.67-1.50	1.60-1.80	1.10-1.20
Glutamic Acid	8.20-12.0	11.20-21.70	5.80-14.80	18.20-18.80	15.30-15.80
Glycine	6.50-7.90	4.00-6.74	3.49-5.90	4.30-4.50	4.20-4.40
Histidine	2.80-4.10	2.10-3.20	1.20-2.27	2.60-2.80	2.80-3.00
Isoleucine	4.70-6.70	3.20-4.04	2.30-5.33	4.50-4.90	4.10-4.40
Leucine	6.20-7.70	5.90-7.05	4.00-9.48	7.80-8.10	7.20-7.50
Lysine	4.20-6.50	4.05-6.60	4.67-8.00	6.40-6.70	6.60-6.90
Methionine	0.10-1.00	1.16-2.40	1.90-2.60	1.30-1.50	1.10-1.30
Phenylalanine	3.80-5.30	3.70-4.61	4.70-7.60	4.90-5.10	5.20-5.40
Proline	6.10-8.40	3.60-5.96	2.40-7.12	5.10-5.40	4.20-4.40
Serine	6.10-8.40	3.05-4.20	2.30-5.97	5.20-5.50	4.70-4.90
Threonine	4.60-6.90	2.80-4.00	2.30-3.96	3.90-4.10	3.60-3.90
Tryptophan	Trace	0.66-0.94	0.93-2.40	1.30-1.40	0.90-1.00
Tyrosine	2.20-4.50	2.80-4.77	4.66-7.30	3.70-3.90	2.70-2.90
Valine	4.70-6.40	4.90-5.10	2.70-6.10	4.80–5.10	4.20-4.50

Studies have shown that WB seeds contain equivalent or higher protein content compared to soybeans. Lysine content was notably higher (6.8% in WB vs. 5.7% in soybean). While, chickpea was found to be low in protein and some essential amino acids. In addition, mineral analysis confirm that WB offers significant amount of iron, zinc, and calcium concentrations. These findings shown enhanced nutritional profile of WB seeds. To achieve a complete amino acid profile, high Sulphur supplements will be required. Despite this limitation, WB seeds are a good source of lysine and threonine. These amino acids are often deficient in cereals-based diets.

The protein fractions were primarily globulins and belong to Psophocarpins A, B, and C. Psophocarpin A found as smaller quantity constituent rich in Sulphur amino acids. However, Psophocarpin B contained anti-nutritional compounds *i.e.,* trypsin inhibitors and lectins (Bepary *et al.,* 2023). The protein efficiency ratio (PER) of WB seed protein was reported to be moderate compared to legume proteins. The estimated PER was 2.14. This moderate quality was contributed by

the lower content of methionine and cysteine in WB seeds.

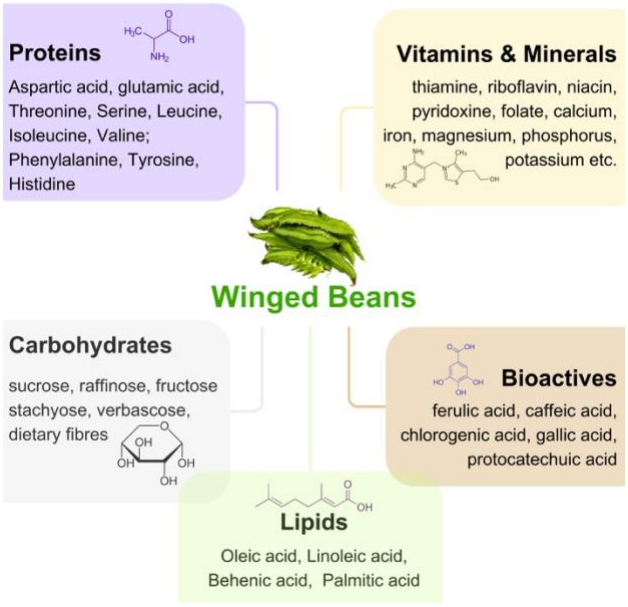

Figure 2. Nutritional composition of WB seeds

2.2. Lipid composition and fatty acids of winged bean seeds

WB seeds have become known for its rich nutritional profile, especially its lipid and fatty acid content. The seeds contain around 17% oil, making them an important source of dietary fat (Garcia *et al.,* 1979). The lipid composition of WB seeds is balanced between saturated and unsaturated fatty acids (Table 3). According to Hishamuddin and Saw (Hishamuddin & Saw, 2022) unsaturated fatty acids accounted for about 70% to 76% of total oil content, rest of the part was saturated fatty acids.

Table 3. Fatty acid composition of winged bean seeds

Fatty Acid (mg/100g of lipid)	WB Seeds (Mature Dried)	Soybean	Chickpea
Arachidic acid (20:0)	0.70-1.70	0.22-0.30	1.00-1.80
Behenic (C22:0)	10.70-18.50	0.10–0.20	Trace
Eicosenoic acid (20:1)	2.50-3.90	-	0.56-0.66
Lignoceric acid (24:0)	2.70-4.20	-	0.09-0.17
Linoleic (C18:2)	19.00-27.90	50.20–54.80	52.90–54.50
Linolenic (C18:3)	0.40-3.20	7.50–9.20	0.70–2.80
Myristic acid (14:0)	Trace-0.10	Trace - 0.10	0.15-0.29
Oleic (C18:1)	27.80-37.10	22.80–24.50	20.90–33.20
Palmitic (C16:0)	5.30-10.90	10.50–11.80	10.80–12.50
Palmitoleic acid (16:1)	Trace-0.40	Trace - 0.10	0.19-0.28
Stearic (C18:0)	2.60-5.30	3.80–4.50	0.90–3.80

The fatty acid composition of WB seed oil has been investigated by Garcia *et al.* (1979). It was found that WB seed oil had similar fatty acid profile compared to peanut oil. Oleic acid (C18:1) was primary monounsaturated fatty acid with 35% to 41% of the total fatty acids. Linoleic acid (C18:2) is an essential polyunsaturated fatty acid that contributed to around 15% to 32% of total lipid profile in WB seed. Parinaric acid is a toxic fatty acid.

Absence of parinaric acid was confirmed which made WB seed oil safe for human consumption. Hishamuddin and Saw (2022) reported Behenic acid (C22:0) is an important saturated fatty acid that was present in more significant amounts (7% to 15%). Palmitic acid (C16:0) constituted about 10% to 14%, while stearic acid (C18:0) was found in lower amount, ranged from 3.5% to 4.3% (Murugiswamy *et al.,* 1983). When compared to soybean oil, WB oil found to have higher long-chain fatty acids and lower linolenic acid. These compositions have improved the stability and shelf life of oils following its potential in food applications (Homma *et al.,* 1983).

2.3. Carbohydrates and dietary fiber in winged bean seeds

Carbohydrate content of WB seeds varies significantly between studies, indicating the effects of genetic diversity, stages of growth, and environmental factors. Bepary *et al.,* (2023) examined 139 genotypes of WB and the average content of carbohydrates was observed to be 26.81% ± 6.88%. In an earlier study by Sajjan and Wankhede (1981), the carbohydrate content was higher, at 42.2%, with 36.2% starch in the percentage. They also found monosaccharides including glucose (1.17%) and fructose (1.5%), as well as oligosaccharides *i.e.,* sucrose, raffinose, stachyose, and verbascose, which accounted for 0.61%. Garcia and Palmer (Garcia & Palmer, 1980) conducted a study with five mature WB varieties and found soluble sugar contents ranging from 9.8% to 13.8%. Their investigations revealed oligosaccharide concentrations ranging from 0.2% to 0.9% (verbascose), 2.2% to 3.6% (stachyose), 1.1% to 2.0% (raffinose), and 5.6% to 8.2% (sucrose). No starch was discovered in mature bean in this investigation, indicating that carbohydrate content varies by genotype and developmental stage.

WB seeds are valued for their high nutritional fiber content, which varies across the plant. Tan and Azrina (2017) found total dietary fiber (TDF) content was 51.81% in seed coat, 22.37% in whole seeds, 21.95% in endosperms, 21.12% in green pods, and 21.12% in canned whole seeds. Insoluble dietary fiber (IDF) comprised the majority of the fiber content, ranging from 21.12% to 50.11%, whereas soluble dietary fiber (SDF) constituted for minor proportion (0.83% to 1.25%). The IDF fraction was high in cellulose (5.07% to 39.34%), hemicellulose (1.5% to 27.19%), and lignin (0.09 to 0.98%).

The structural carbohydrate content comprises mainly insoluble dietary fiber (IDF), which constitutes 21-50% of total fiber. This is significantly higher than the soluble fiber fraction (Aulia H *et al.,* 2024). This high IDF content highlights the digestive health benefits related to WB consumption. Additionally, oligosaccharides such as raffinose and stachyose occur at lower levels, suggested potentially reduced flatulence problems (Garcia & Palmer, 1980).

Processing processes like dehulling, soaking, and sterilization may affect the dietary fiber content, with dehulling lowering total fiber content and soaking and sterilization increasing SDF while decreasing IDF, stachyose, verbascose, and hemicellulose levels. The high insoluble fiber content of WB seeds supports digestive health by maintaining regular bowel movements and preventing constipation, while soluble fiber controls blood sugar levels and lowers cholesterol. Oligosaccharides *i.e.,* raffinose, stachyose, and verbascose, although present in trace amount, have prebiotic effects by promoting the growth of beneficial bacteria in the gut. These characteristics make WB seeds an important dietary component for improving digestion and reducing diseases associated with low fiber consumption.

2.4. Vitamins and minerals in winged bean seeds

All the parts of the WB plant *i.e.,* pods, seeds, leaves, flowers, and tubers are edible and high in essential vitamins and minerals (**Table 4**). Bepary *et al.* (2023) have reviewed different parts of the WB plant. The leaves of the WB are particularly abundant in vitamin A, with concentrations ranging from 5240 to 20800 IU.

Seeds does not contain vitamin A. Both the pods and leaves are excellent sources of vitamin C. The leaves contain between 14.5 to mg/100g, while the pods provide approximately 18.3 mg/100g. Seeds contain trace amount of vitamin C. WB seeds are rich in several B-vitamins, including thiamine, riboflavin, niacin, pyridoxine, and folate of 08-1.7mg, 0.2-0.5mg, 3.1-4.6mg, 0.1-0.25mg, and 25.6-63.5µg, respectively. These vitamins play pivotal roles in energy metabolism, red blood cell formation, and neurological health. The seeds were found to be high in different minerals *i.e.,* calcium (102-850mg), iron (4.9-16mg), magnesium (178-372mg), phosphorus (310-637mg), potassium (100-1090), sodium (10-50mg), zinc (2.6-7.4mg), manganese (1.9-8.5mg), and copper (1.1-5.2mg).

Table 4. Composition of minerals and vitamins in different parts of winged bean

Component (mg)	WB Seeds (Mature Dried)	WB Pods	WB Leaves	Soybean	Chickpea
Calcium	80-370	45–78	113–440	225–300	117–284
Copper	1.50-2.00	0.20–0.40	0.30–7.10	1.10–1.90	0.60–0.90
Iron	8.50–18	1.2–2.8	2.50–18.60	8.5–16.40	4.70–9.98
Magnesium	110–255	25–48	28–65	240–280	121–203
Phosphorus	325–610	35–58	25–98	620–695	284–560
Potassium	370–1150	225–385	130–580	1410–1797	981–1437
Zinc	3.20–5.00	0.60–1.20	1.10–7.30	2.70–4.90	1.51–4.10
Vitamin A (IU)	-	225–900	5240–20800	22–25	-
Vitamin C	Trace-0.50	21-37	14.5-128	2.00-4.66	1.35-1.65
Thiamine (B1)	0.85–1.70	0.12–0.28	0.25–3.60	0.66–1.28	0.48–0.55
Riboflavin (B2)	0.25–0.50	0.06–0.12	0.15–2.60	0.12–0.29	0.21–0.26
Niacin (B3)	2.20–4.60	0.60–1.20	1.20–15	1.60–2.10	1.22–1.72
Vitamin B6	0.15–0.28	Trace - 2	Trace - 1	0.35-0.45	0.30–0.38
Folate (µg)	25.60–95	60-67	-	267-375	206-299
Vitamin E	1.50–22.80	0.20–0.50	1.80–4.50	0.80-1.20	1.91-2.24

2.5. Bioactive compounds of winged bean seeds

WB seeds are recognized for their rich composition of bioactive compounds, which contribute to their nutritional and therapeutic properties. These compounds include phenolic acids, flavonoids, fatty acids, and bioactive peptides, each playing distinct roles in health promotion.

2.5.1. Phenolic compounds and flavonoids

WB seeds are recognized for their abundance of bioactive compounds, particularly phenolic acids and flavonoids, which contribute to their nutritional and health-promoting properties. In WB seeds, significant phenolic acids identified *i.e.,* ferulic acid, caffeic acid, chlorogenic acid, gallic acid and protocatechuic acid. The concentrations of these compounds can vary widely depending on factors *i.e.,* genotype, environmental conditions, and analytical methods used for assessment. According to Mohanty *et al.* (2013), gallic acid has been detected in WB seeds at concentrations ranging from 0.09 to 3.49 µg/g, while kaempferol, a flavonoid known for its antioxidant properties, has been reported in amounts between 1.07 and 790.5 µg/g. Although specific quantitative data on other phenolic acids, such as ferulic acid, caffeic acid, chlorogenic acid, and protocatechuic acid, remain limited, phytochemical screenings have confirmed their presence. Similarly, flavonoids like quercetin and rutin have been identified in the seeds, though detailed concentration data are scarce (Bassal *et al.,* 2020). Given the considerable variation in bioactive compound levels among different genotypes and environmental

conditions, further research is necessary to establish a more comprehensive understanding of their distribution and potential health benefits in WB seeds.

2.5.2. Fatty Acids

WB seeds serve as a valuable source of essential fatty acids, contributing to their nutritional significance (Kavitha *et al.,* 2023). Among the dominant fatty acids identified, palmitic acid accounts for 1.48% of the total composition. As a saturated fatty acid commonly found in plants, it plays a role in various metabolic functions. Oleic acid, a monounsaturated fatty acid known for its positive impact on cardiovascular health, constitutes 6.68% of the seed's lipid profile. Linoleic acid is an essential polyunsaturated omega-6 fatty acid important for human health. It was found to be 4.80% in WB seeds. Additionally, linolenic acid content was 0.30%. The seeds also contain 0.88% stearic acid and 1.18% behenic acid. The fatty acid profile of WB is similar to that of soybean and peanut, with a high amount of unsaturated fatty acids (Messina, 1999). WB are relatively low linolenic acid and high behenic acid suggested good oxidative stability (Bepary *et al.,* 2023). The presence of beneficial fatty acids remained stable after thermal processing. This indicated the feasibility of WB for cooked and baked products (Olaifa *et al.,* 2022a).

Ekpenyong and Brochers (1980) highlighted the potential of WB seeds as a nutritious food source rich in essential fatty acids. Mohanthy *et al.* (2015) stated that the unsaturated fat content in mature WB seeds is higher (66%) compared to young seeds (39%). Thermal processing methods like boiling and sterilization do not significantly affect the composition of these fatty acids, maintaining their nutritional value post-cooking.

2.5.3. Bioactive peptides

WB seeds have emerged as a promising source of bioactive peptides with notable angiotensin-I-converting enzyme (ACE) inhibitory and antioxidant activities. Research indicates that enzymatic hydrolysis of WB seed proteins can generate peptides with significant ACE inhibitory properties. Yea *et al.* (2014), found that proteolysis of WB seed proteins led to ACE inhibition reaching up to 78.5% after 12 h of hydrolysis. This finding suggests that these hydrolysates could play a role in managing hypertension by inhibiting ACE, a crucial enzyme involved in blood pressure regulation. Two specific peptide sequences, YPNQKV and FDIRA, have been identified as bioactive components, further highlighting the potential of WB seeds as a functional food ingredient.

Beyond ACE inhibition, WB seed protein hydrolysates have also demonstrated remarkable antioxidant properties. The same study reported that these hydrolysates exhibited high antioxidative effects, as confirmed through various assays, indicating their ability to counteract oxidative stress-related damage. Hlosrichok and Aunpad (2023) explored the impact of gamma-ray irradiation on WB seeds. Their study revealed that protein extracted from irradiated seeds, when subjected to enzymatic hydrolysis, exhibited enhanced antioxidant activity compared to non-irradiated controls. This improvement is attributed to the generation of peptides with potent free radical scavenging properties.

These findings highlight the potential of WB seed-derived peptides as natural substances for controlling blood pressure and reducing oxidative stress. Incorporating them into functional foods or nutraceutical formulations could deliver significant health benefits, specifically in the prevention and treatment of hypertension and cardiovascular disorders.

2.6. Antinutritional factors in winged bean seeds

2.6.1. Protease Inhibitors

Protease inhibitors (trypsin and chymotrypsin inhibitors) are found to be common in WB seeds. These compounds affect protein digestion by inhibiting proteolytic enzymes in the digestive tract. These results in reduction in protein availability (**Table 5**). However, these inhibitors can be significantly reduced through heat treatment, soaking, and fermentation. Trypsin inhibitors in WB seeds are also found to be reduced by microwave heat

treatment (2450 MHz for 3-5 min) (Mahalakshmi *et al.,* 2025).

Table 5. Antinutrients and allergens in winged bean seeds

Component	WB Seeds	Property
Phytic acid (mg of phosphorus/g of bean)	6.10-7.52	Binds and reduce minerals absorption
Tannin (mg of D-catechin/g of bean)	0.30-7.50	Binds and reduce protein digestibility and enzyme activity
Lectin (mg/100 mg psophocarpin B)	2.30	Cause gut irritation, reduces nutrient absorption, may agglutinate RBCs
Oxalate (%)	0.50	Binds and reduce calcium to form insoluble salts
Saponin (%)	0.60	Affect gut lining, has haemolytic effects, bitter taste
Trypsin Inhibitors (TUI/mg)	34.35-78.33	Inhibit trypsin, reducing protein digestion
Non protein trypsin Inhibitors (TUI/mg)	2.56-6.79	
Chymotrypsin Inhibitors (CIU/mg)	598-868	Inhibit chymotrypsin, affecting protein digestion
Hemagglutinating Activity (HU/mg of bean)	40-320	Reflects lectin activity; causes red blood cells to clump (if not deactivated)
Allergens		
Winged Bean Albumin 1 (WBA-1) (% of protein)	15	Water soluble protein, may cause allergen similar to other legume albumin
Psophocarpin A (g/kg of seed)	7	Fractions of WBA-1
Psophocarpin B (g/kg of seed)	30-50	
Psophocarpin C (g/kg of seed)	65	

2.6.2. Phytic Acid

Phytic acid cause chelation of minerals and forms complexes. Humans do not contain endogenous phytase. These complexes are resistant to hydrolysis by human digestive enzymes. This results in reduced absorption of iron, zinc, and calcium, potentially leads to deficiencies. This is more common in regions where WBs are a staple food (Chudasama *et al.,* 2025). High phytate-to-iron molar ratios above 1:1 can significantly reduce iron absorption, while ratios above 10:1 for zinc impair its bioavailability in legumes (Mohanty *et al.,* 2013).

WB seeds contain significant levels of phytic acid. Kantha *et al.* (1986) reported phytic acid content in WB seeds ranged from 1.0-1.7% of dry weight, depending on the variety and analytical method. Mohanty *et al.* (2021) reported phytic acid at 0.18-0.2%, while Bepary *et al.* (2023) noted a range of 4.09-9.96%. This variability suggested differences in cultivar, processing, or analytical methods. It highlights the need for processing to reduce its antinutritional effects. While phytic acid is an antinutrient, it also exhibits beneficial properties *i.e.,* antioxidant activity and potential anticancer effects. It has ability to chelae

excess iron and reduces oxidative stress. Thus, complete elimination of phytic acid may not be desirable. Processing methods should aim to balance phytic acid reduction with retention of these benefits.

2.6.3. Tannins

Tannins in WB seeds are primarily condensed tannins (proanthocyanidins). They are polymeric flavonoids synthesized via the phenylpropanoid pathway. These compounds bind to proteins and minerals through hydrogen bonding and hydrophobic interactions. As a result, indigestible complexes are formed, which reduce nutrient bioavailability. Condensed tannins consist of flavan-3-ol units (catechin, epicatechin) linked by carbon-carbon bonds. Their hydroxyl groups form stable complexes with digestive enzymes (trypsin) and dietary proteins. This resulted in inhibition of proteolytic activity (Kotaru, 1987; Singh *et al.,* 2023). In WBs, tannins are localized in tannosomes (specialized organelles) within leaf and seed tissues, visible as blue deposits when stained with DMACA (Chankaew *et al.,* 2022).

Total condensed tannin content in WB leaves and seeds ranged from 1.35-6.75mg/g. These values may vary depend on the accession and post-processing conditions. On the other hand, monomeric catechin content in the control lines was observed at up to 4.8mg/g dry weight. This value drops significantly with targeted gene silencing of anthocyanidin synthase (ANS). Combine these results stated over 70% reduction in CT content (Kotaru, 1987; Singh *et al.,* 2023).

Localization of tannins in tannosomes within various tissues (including seeds), visible as blue deposits when stained with DMACA. This points to their initiation of synthesis in the chloroplast before accumulation in vacuoles (Singh *et al.,* 2023). The presence of high CT levels is linked to lower nutritional quality. These polyphenols have ability to form insoluble complexes with minerals and macronutrients. They also impart antioxidant capacity to the seeds, which is significant for potential health benefits (Bassal *et al.,* 2020). Gene silencing of the ANS transcript have been found effective to reduce CT levels. These methods have potential for breeding or biotechnological interventions a viable approach to enhance the nutritional value of WB seeds for food applications (Kotaru, 1987; Singh *et al.,* 2023).

2.6.4. Lectins

Lectins in WB seeds are a class of glycoproteins that belong to both acidic and basic lectin groups. These proteins specifically bind to carbohydrates (particularly β-D-galactosides) with different affinities. This depends on the lectin isoform present in the seed. The major lectins found in WB seeds have molecular masses around 54000 (Kortt, 1985). They are rich in acidic and hydroxy amino acids. Lectins from WB seeds accumulate human erythrocytes (red blood cells). They found to have toxic effects, when consumed raw. It indicates a significant anti-nutritional factor (Higuchi *et al.,* 1988; Kortt, 1985).

Additionally, active lectins may stimulate or disrupt immune responses. They can potentially cause gastrointestinal disturbances shortly after ingestion due to their resistance to digestive enzymes and gastric conditions (Ayyagari *et al.,* 1993; Panacer & Whorwell, 2019). Importantly, lectins are heat-labile proteins. Food processing method like boiling, can effectively inactivate lectin activity. However, heating legume seeds at relatively low temperatures (70°C) is insufficient to eliminate lectin activity. Complete inactivation generally requires boiling (95-100°C) for at least 10-60min. High moisture content and hydration conditions significantly improves efficacy. Dry roasting or steaming can also be used to didactive lectins but must be carefully controlled for optimal safety (Pusztai & Grant, 1997).

2.6.5. Oxalates

Oxalates are naturally occurring anti-nutritional compounds present in WB seeds. They exist mainly as soluble and insoluble salts of oxalic acid. These compounds have a high affinity for divalent cations. They can from insoluble calcium oxalate complexes that significantly decrease calcium bioavailability and may increase the risk of kidney stone

formation (Siener *et al.,* 2006). Oxalate concentrations in WB seeds ranged between 340 and 597 mg/100 g of seed tissue. This can categorize them as a legume with comparatively high oxalate content (Bepary *et al.,* 2023; Ibuki *et al.,* 1983). The presence of oxalate strongly inhibits calcium absorption. These demonstrated a negative correlation between oxalate levels and calcium dialysability *in vitro* (Das *et al.,* 2022).

Processing methods *i.e.,* soaking, boiling, sprouting, fermentation, and roasting are common for WB seeds to reduce their anti-nutritional factors, including oxalates (Bepary *et al.,* 2023). Quantitative reductions in oxalate specifically in WB seeds remain scarce. Research on legumes and vegetables indicated that soaking and boiling can lead to decreases in soluble and total oxalate content upto 65% and 97%, respectively (Chai & Liebman, 2005; Salgado *et al.,* 2023). Although direct experimental confirmation of these reductions in WB seeds is still required, it is adequate to note these outcomes given the biochemical similarity across legumes. Future targeted research to study oxalate dynamics specific to WB processing is necessary to optimize further protocols.

2.6.6. Saponins

Saponins are naturally occurring glycosides present in WB seeds. They are characterized by their amphiphilic structure that contributes to bitterness and foaming properties. These compounds are known for their biological activities with potential cholesterol-lowering effects. Excessive intake may cause discomfort of the gastrointestinal tract and interfere with nutrient absorption (specifically of lipids).

WB seeds reported saponin contents varied by cultivar and maturity, within the range of 1-3% of seed dry weight (Bepary *et al.,* 2023; King & Puwastien, 1987b). Thermal processing methods such as boiling, roasting, and soaking have been demonstrated to significantly reduce saponin levels in other legumes (Bepary *et al.,* 2023). Soaking seeds in water followed by boiling for 30-60 min can reduce saponin content by 40-70% due to leaching and thermal degradation of these compounds. These treatment steps also enhance protein digestibility and reduce bitterness.

Detailed studies on saponin reduction in WB seeds specifically are limited. These promising findings suggests that standard food processing methods are effective at mitigating saponin-associated anti-nutritional effects. Further research focused on optimizing processing parameters specific to WB saponins would help to increase nutritional benefits with balanced sensory properties.

3. Processing methods and applications of winged bean seeds

One of the principal challenges in expanding WB seed utilization is the high degree of hardseededness. It is a phenomenon caused by the water-impermeable seed coat, which limits germination and affects food processing (Han *et al.,* 2022). Mechanical scarification (sandpaper abrasion, sulfuric acid treatment) has proven most effective to decrease hardseededness. This also increases germination and reduce processing time. However, hot water and ultrasonic treatments remain ineffective, suggested the need for innovation in pre-processing technologies (Han *et al.,* 2022). Overall, the necessity for intensive pre-treatment is a major barrier to scaling up WB in food applications.

Researchers have investigated a variety of processing methods *i.e.,* cooking, drying, soaking, sterilization, and fermentation (**Figure 3**) to improve the nutritional content, functional characteristics, and digestibility of WB seeds. Researchers also examined at how these treatments affect antinutritional factors, bioavailability, and sensory qualities to optimize their application in food products. Findings of several studies on the processing and applications of WB seeds in the food industry are summarized in **Table 6**.

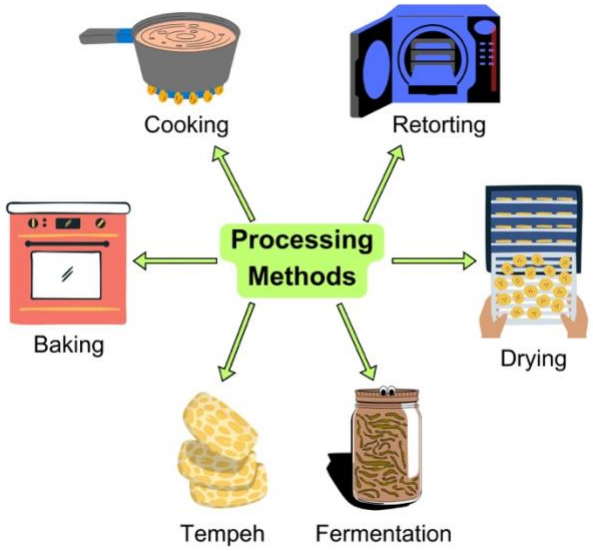

Figure 3. Conventional methods for the processing of WB seeds

Though limited, research work on WB demonstrated that heat treatments (cooking and baking) improved seed softness and digestibility. They significantly improved protein content and decrease anti-nutritional factors (oxalate and phytate) (Olaifa *et al.,* 2022a). Sterilization and fermentation methods further increased nutrient bioavailability. They facilitated the development of different WB food products *i.e.,* analog meat substitutes and gluten-free baked products. Modern applications explored WB seed milk, tofu, tempeh, and fortified snacks.

Table 6. Application of WB seeds in food industry

Processing techniques	**Findings**	**Potential applications**	**References**
Retorting effects on nutrition	Higher F_0 sterilization (5, 7, 10) increased moisture and carbohydrates but reduced protein. Ash and fat remained unaffected.	Canned winged bean products with controlled nutritional retention.	(Setiawan *et al.,* 2023)
Heat treatment on enzyme inhibitors	75% activity of trypsin and α-chymotrypsin inhibitors lost in 60s; complete inactivation in 6 min. Heating was mostly below 100°C.	Improves digestibility and reduces anti-nutrients in processed winged bean products.	(De Lumen & Belo, 1981)

Functional properties of winged bean flour	Autoclaving (10 min, 1 kg/cm²) reduced trypsin inhibitors from 130 to 5 TIU/mg. Heat lowered nitrogen solubility but increased water (+38%) and fat (+57%) absorption. Emulsification and foam capacity decreased. NaCl (0.4M) improved emulsification.	Formulating heat-treated winged bean flour for bakery, dairy, and meat analogue applications.	(Narayana & Narasinga Rao, 1982)
Drying effects on chemical & sensory traits	No interaction between temp. and drying time except on vitamin C and yield. Best drying conditions was 60°C for 20 hours.	Production of dried winged bean for ready-to-cook or snack applications.	(Asgar *et al.,* 2022)
Quick-cooking processing	Boiling reduced cooking time by 90%. Quick-cooked bean had better texture and flavour. No significant nutrient loss.	Developing quick-cooking winged bean for convenience foods.	(Rockland *et al.,* 1979)
Soaking & boiling effects	Increase in pH; leaching of solid materials. Alkaline-treated bean softened better but darkened. Resoaking post-boil had no protein impact.	Alkaline soaking methods for improving texture in bean-based dishes.	(Sambudi & Buckle, 1991)
Chemical, thermal, and morphological properties	Pretreatment (boiling for 30 min) reduced carbohydrate, protein, fat, and ash, but increased water retention. Thermal stability indicated material applications (e.g., coatings).	Use in biodegradable coatings and food packaging to extend shelf life.	(Riwayati *et al.,* 2022)
Processing full-fat winged bean flour	Sodium bicarbonate soaking (0.5-1%) and boiling (30-45 min) helped hull removal. Dry dehulling had low efficiency (14-22%). Trypsin inhibitors reduced by 30-40%. Flour stored well for 4 weeks.	Producing full-fat winged bean flour for baking and protein-enriched food products.	(Kailasapathy *et al.,* 1985)
Processing (baking & boiling) effects	Boiling (100°C, 20 min) & baking (250°C) increased crude protein (baked: 17.93%, boiled: 19.59%, control: 12.55%). Tannins increased but oxalates (-22%) & phytates (-20%) reduced.	Enhancing protein and nutritional value in baked and boiled legume products.	(Olaifa *et al.,* 2022b)

Cooking effects on antinutrients & antioxidants	Cooking significantly reduced phytates, tannins, and cyanogenic glycosides in some varieties. Phenolic content increased in T125 variety. No significant antioxidant changes.	Promoting cooked winged bean varieties for nutraceutical and functional food applications.	(Maimako *et al.,* 2022)
Winged bean–soy tempeh	50:50 ratio improved protein (17.41%) and antioxidants (51.8%). Highlighted balance between nutrition and consumer preference.	Developing alternative tempeh formulations with enhanced nutrition.	(Maitresya & Surya, 2023)
Gastrointestinal effects of winged bean milk	Ungerminated seeds had higher raffinose family oligosaccharides (RFOs), leading to flatulence. Germination reduced RFOs and digestive discomfort.	Producing germinated winged bean milk with improved digestibility.	(King & Puwastien, 1987a)
Winged bean-Moringa seed tempeh	Optimal 80:20 ratio gave high protein (53.41%), fat (25.57%), and good sensory qualities (texture: 4.3/5, aroma: 4/5).	Creating high-protein, nutrient-dense tempeh alternatives.	(Puspitasari *et al.,* 2023)

3.1. Soaking

Soaking involves immersion of WB seeds in water (about 12 h). This activates endogenous phytase enzymes to hydrolyze phytic acid into lower inositol phosphates with reduced mineral-binding capacity. Additionally, phytic acid can leach into the soaking water, further lowering its content. Studies on legumes suggested soaking can reduce phytic acid by 40-60% (Hurrell, 2003; Sarkhel & Roy, 2022), with optimal conditions at room temperature and pH 4-6 gave improved phytase activity.

3.2. Germination

Germination involves allowing the seeds to sprout for 48-72 h at 25-30°C. The process activates phytase to break down phytic acid and release inorganic phosphate. It was found to reduce phytic acid by 35-70% in legumes (Bektaş & Ertop, 2021). It also enhanced mineral solubility as a result of the seed matrix alteration.

3.3. Fermentation

Fermentation utilizes microorganisms like lactic acid bacteria or yeasts to produce phytases or to create acidic environments that promote phytate hydrolysis. This can reduce phytic acid by 56-96% in legume products. Fermentation of WB flour using *Lactobacillus plantarum* found to be achieved significant reductions in phytic acid upto 48.33% (Ghamry *et al.,* 2023). The acidic environment (pH < 5) enhances phytase efficacy, improving mineral bioavailability (Hummel *et al.,* 2020).

Significant risk of allergenicity is present in WB, which is common for all protein-rich legumes. Allergenic proteins have been isolated in both raw and boiled WB. Multiple protein bands reactive to IgE were found from allergic individuals during skin prick tests (Lusiana *et al.,* 2023). While documented food allergy cases are rare, these findings highlight safety screening for populations with legume sensitivities. It further requires investigation of hypoallergenic processing alternatives.

WB flour or blends contributed positively to protein-energy malnutrition management. Protein efficiency ratios (PER) of these blends

were similar to those of milk protein and improved compared to groundnut-based products. Černý and Addy (1973) carried out clinical studies of children with kwashiorkor. It was found that diets incorporated with WB flour produced recovery rates comparable to those based on skim milk. There were no adverse outcomes reported. Despite positive results, longer-term trials are needed to confirm efficacy and safety. These are specifically concerned regarding allergenicity and chronic consumption impacts.

4. Future prospects and challenges

WB seeds offer significant potential as a sustainable, high-protein source that can help address global food security problems. To improve their commercial viability and consumer acceptance, several kinds of challenges need to be resolved despite their nutritional and functional benefits. The future of WB seeds is dependent on developments in processing technology and focused research in product development to address potential health issues related to antinutritional factors and allergenicity. Efficient and scalable manufacturing processes are required to optimize the functional properties and nutritional quality of WB seeds while maintaining their economic feasibility in the food industry. Current methods, including as soaking, boiling, autoclaving, and fermentation, have showed success in lowering antinutritional factors and enhancing digestibility. However, these conventional methods often result in nutritional loss, prolonged processing cycles, and limited scalability.

Future research must focus on novel processing methods such as high-pressure processing (HPP), pulsed electric field (PEF), and ultrasound (US) treatments to improve protein bioavailability while preserving heat-sensitive nutrients. Enzymatic treatments can also be employed to systematically hydrolyze undesired compounds while preserving the structural integrity of proteins and starches. Cold plasma technology can provide novel methods to inactivate antinutritional compounds and microbial contaminants without applying excessive heat. These innovations have the potential to significantly enhance the overall quality, shelf life, and safety of WB-based products. These can contribute to increase WB products value in the global market. The development of innovative food products containing WB seeds has the potential to extend their application further. Currently, WB seeds are being investigated for value addition in tempeh, flour, plant-based milk, and protein isolates. However, it has more potential for additional innovation in the other areas. WB seeds have a high protein content and an adequate amino acid profile, resulting in an excellent alternative for plant-based meat and dairy substitutes. Extrusion technology and fermentation could be used to improve texture and flavor profiles, comparable to developments in soy and pea protein-based products. Because of their antioxidant and bioactive qualities, WB seeds can be added to functional foods like protein-rich drinks, high-fiber baked products, and sports nutrition formulations to provide further health benefits.

5. Conclusions

WB is a nutritionally rich, sustainable, and versatile legume that has multiple applications in the food industry. Their high protein content, essential amino acid composition, and bioactive properties make them an excellent choice for addressing global hunger and food security concerns. Despite its potential, limitations like consumer acceptability, antinutritional factors, and scalability of processing methods must be resolved. Future research should focus on improving processing procedures, developing new food formulations, and evaluating the safety and allergenicity of WB seed-based products. Various processing methods *i.e.,* thermal treatment, fermentation, and novel approaches *i.e.,* pulsed electric field (PEF) and enzymatic hydrolysis, can be used in future to improve nutritional content and functionality. With advancing food technology developments and effective market position, WB seeds have the potential to become a valuable functional food ingredient, contributing to sustainable and

healthy diets throughout the world. WB seeds represent a highly promising, but underexplored, plant protein source. Modern processing can mitigate antinutritional factors, and clinical evidence supports both efficacy and safety in human diets. Nevertheless, challenges remain in seed hardness, industrial scalability, and allergenicity assessment. Future research should prioritize breeding for softer, low anti-nutrient varieties, optimize scalable processing protocols, and conduct comprehensive allergenicity and clinical nutrition trials to facilitate for broader adoption in food systems.

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