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WINGED BEAN (PSOPHOCARPUS TETRAGONOLOBUS): PHYTOCHEMISTRY, PHARMACOLOGICAL ACTIVITIES AND PHARMACEUTICAL POTENTIAL

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ABSTRACT

Psophocarpus tetragonolobus (winged bean) is an underutilized tropical leguminous crop of exceptional nutritional value and growing pharmaceutical interest. Its seeds, pods, leaves and tubers are rich sources of proteins, essential amino acids, dietary fiber, vitamins, minerals and diverse bioactive phytochemicals, including phenolics, flavonoids, saponins, terpenoids, lectins, bioactive peptides and phytosterols. These phytoconstituents exhibit a broad spectrum of pharmacological activities, including antioxidant, anti-inflammatory, antimicrobial, antidiabetic, cardioprotective and potential anticancer effects through mechanisms such as free radical scavenging, modulation of inflammatory pathways and inhibition of carbohydrate hydrolyzing enzymes. Recent advances in phytochemical characterization, extraction technologies and genomic resources have further highlighted the potential of winged bean for the development of nutraceuticals, functional foods, pharmaceutical formulations and novel drug delivery systems. Despite encouraging preclinical evidence, its clinical translation remains limited owing to insufficient toxicological and pharmacokinetic data and the lack of well-designed human clinical studies. This review comprehensively summarizes the phytochemical composition, pharmacological activities and pharmaceutical potential of P. tetragonolobus, while discussing current challenges and future research directions. Overall, winged bean represents a nutritionally valuable and pharmacologically promising legume with considerable potential for future nutraceutical and pharmaceutical development, warranting further clinical validation and translational research.

KEYWORDS: Psophocarpus tetragonolobus; Winged bean; Phytochemistry; Pharmacological activities; Functional foods; Nutraceuticals.

1. INTRODUCTION

The winged bean (Psophocarpus tetragonolobus (L.) DC.), often hailed as the "soybean of the tropics," represents a paradigm of an underutilized yet exceptionally versatile legume with profound implications for global food security, nutrition and pharmaceutical innovation (1, 2). Belonging to the Fabaceae family, this fast-growing, climbing perennial is indigenous to the Old-World tropics, with significant cultivation across Southeast Asia, Papua New Guinea and parts of Africa (3, 4). Its common names are four angled bean or Goa bean derive from the distinctive winged edges of its edible pods. Despite its remarkable nutritional profile and documented ethnomedicinal applications, P. tetragonolobus remains largely neglected in mainstream agriculture and pharmacology, a status that belies its immense potential as a multi utility crop (5, 6). Its significance as an underutilized medicinal legume stems from a confluence of agronomic resilience and biochemical richness. More critically, virtually every part of the plant the leaves, flowers, green pods, mature seeds and even the tuberous roots are edible and nutritionally dense (7, 8). All edible plant parts of winged bean, including seeds, tubers, leaves and immature pods, possess distinct nutritional characteristics that collectively make the crop one of the most nutrient-dense legumes (Table 1). Among these, the seeds are particularly rich in protein and lipids, whereas the tubers, pods and leaves contribute valuable carbohydrates, vitamins and essential minerals (4, 6, 9). This comprehensive nutritional package makes it a potent tool against protein-energy malnutrition and micronutrient deficiencies, especially in resource-limited tropical regions. Beyond its macronutrient and micronutrient content, the winged bean is a treasure trove of bioactive phytochemicals that form the foundation of its pharmacological promise. Comprehensive phytochemical profiling has identified a diverse array of secondary metabolites, including phenolic compounds (such as flavonoids and tannins), saponins, terpenoids, steroids and alkaloids (10-12). These compounds are not merely incidental; they are the molecular mediators of the plant's biological activities. For instance, the high concentration of total phenolics and flavonoids directly correlates with its potent antioxidant capacity, as demonstrated in numerous studies using assays like DPPH (12, 13). This antioxidant property is a critical first line of defense against oxidative stress, a key pathological driver in chronic diseases like diabetes, cardiovascular disorders and cancer. Furthermore, specific compounds like pterostilbene a stilbenoid also found in blueberries have been associated with a wide spectrum of pharmacological actions, including antidiabetic, anti-inflammatory and neuroprotective effects (14), suggesting their potential presence or structural analogues in P. tetragonolobus may contribute to its observed bioactivities. The traditional medicinal uses of the winged bean provide a compelling ethnobotanical roadmap for its modern scientific validation. Across its native range, various plant parts have been employed in folk medicine to treat a spectrum of ailments. Extracts from leaves and seeds have been used as a diuretic and to alleviate mouth ulcers, while the plant has also been applied topically for skin conditions and used to manage symptoms of smallpox (5). Perhaps most significantly, given the global burden of metabolic disease, it has a history of use in managing blood sugar levels, a claim now being rigorously investigated through modern scientific methods (15). This bridge between traditional knowledge and contemporary research underscores the value of ethnopharmacology in guiding the discovery of novel therapeutics from natural sources. This convergence of exceptional nutrition, rich phytochemistry, validated traditional use and emerging scientific evidence has catalyzed a surge of current pharmaceutical interest in P. tetragonolobus. Recent research has moved beyond basic compositional analysis to mechanistic investigations of its health benefits. Studies have confirmed its extracts possess significant anti-inflammatory properties by modulating key inflammatory pathways in macrophage cell lines (16). Its antidiabetic potential is being actively explored, with research focusing on how its bioactive compounds modulate glycemic control, potentially offering a natural alternative or adjunct to synthetic drugs (15). The identification of its complete telomere-to-telomere genome assembly and a suite of genomic tools now provides an unprecedented opportunity to link specific genes to the biosynthesis of these valuable phytochemicals, paving the way for targeted crop improvement and bioproduction strategies (7, 17). Given this dynamic landscape of rediscovery and scientific validation, the primary objective of this review is to provide a comprehensive, up to date synthesis of the current knowledge on Psophocarpus tetragonolobus, with a specific focus on its phytochemistry, pharmacological activities and pharmaceutical potential. The scope encompasses a detailed examination of its nutritional composition, a systematic cataloguing of its identified phytochemical constituents across different plant parts and a critical evaluation of the experimental evidence supporting its diverse biological activities, including antioxidant, anti-inflammatory, antidiabetic and antimicrobial effects. By integrating findings from ethnobotany, food science, phytochemistry and pharmacology, this article aims to highlight the winged bean not just as a food crop, but as a promising and sustainable source of novel bioactive compounds for the development of functional foods and future pharmaceuticals, thereby advocating for its greater recognition and exploitation in the quest for global health and nutritional security.

Table 1. Nutritional composition of different plant parts (per 100 g dry weight unless specified)

Plant Part	**Protein (%)**	**Fat (%)**	**Carbohydrate (%)**	**Fiber (%)**	**Key Minerals & Vitamins**	**References**
Seeds	29.3–37.0	14.0–18.0	30.0–35.0	4.0–6.0	Rich in Ca, Fe, Zn; B-complex vitamins	(6, 18)
Tubers	8.0–12.0	0.5–1.5	70.0–80.0	1.0–2.0	High in K, moderate Ca; low fat	(18)
Young Pods	2.5–4.0 (fresh)	0.2–0.4 (fresh)	5.0–7.0 (fresh)	1.5–2.5 (fresh)	Good source of vitamin C, β-carotene	(11)
Leaves	~ 5.85 g	Low	Moderate	Moderate	Contains folate, vitamin A precursors	(19) &(USDA)

2. Phytochemical Composition

The phytochemical composition of winged bean, represents a sophisticated biochemical arsenal that underpins its dual role as a nutrient dense food and a source of pharmacologically active compounds with direct relevance to human health. A systematic analysis of its secondary metabolites reveals a complex; plant part specific distribution of bioactive molecules whose synergistic and individual actions contribute to its documented health benefits. The distribution and biological significance of the major phytochemical classes identified in winged bean are summarized in Figure 1.

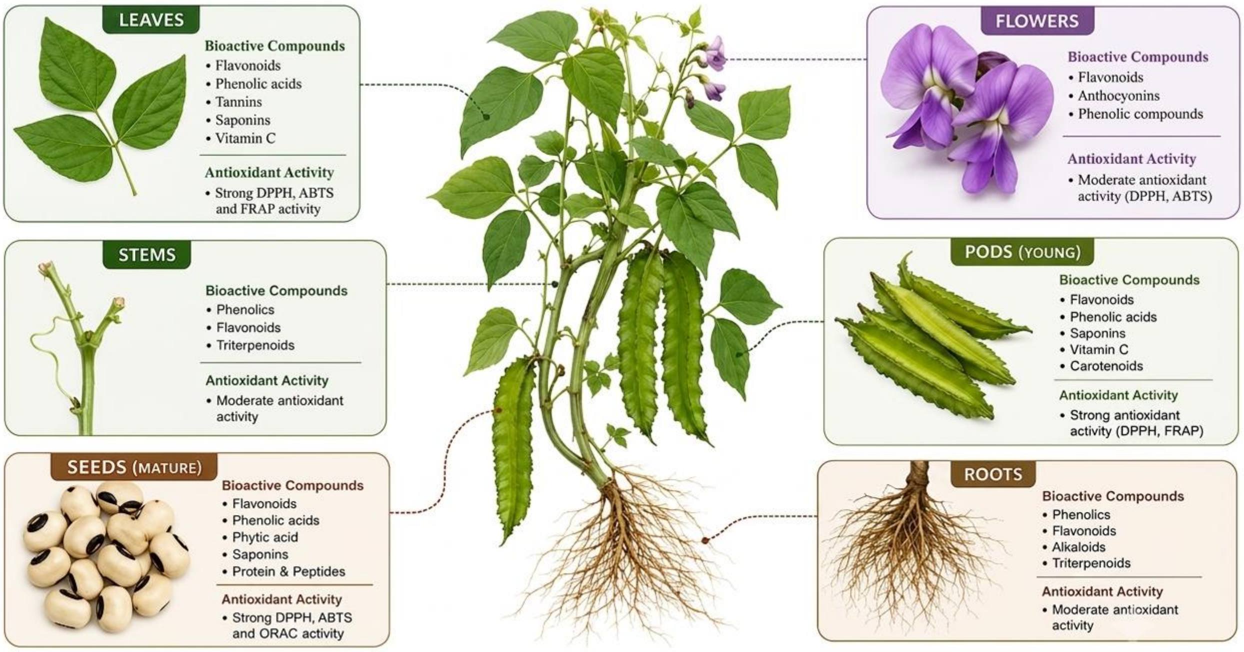

Figure 1. Bioactive compounds across different plant parts of Psophocarpus tetragonolobus.

2.1 Phenolic Compounds
Phenolic compounds are the most abundant and functionally significant phytochemicals in winged bean, serving as primary contributors to its antioxidant capacity. Quantitative analyses have revealed considerable variation in total phenolic content (TPC) across different genotypes and plant organs. For instance, seed extracts have been reported to contain TPC ranging from 15.2 to 42.8 mg gallic acid equivalents (GAE) per gram of dry weight (13). Young pods also exhibit high phenolic levels, which directly correlate with their free radical scavenging activity (11). The primary mechanism of action for the following compounds involves the donation of hydrogen atoms or electrons to neutralize reactive oxygen species (ROS), thereby mitigating oxidative stress a key pathological factor in chronic human diseases such as atherosclerosis, neurodegeneration and cancer (16). This robust antioxidant defence system is a critical component of the winged bean's health-promoting properties.

2.2 Flavonoids
Flavonoids, a major subclass of phenolics, are particularly abundant in winged bean seeds, leaves and young pods (11). Their presence has been confirmed through standard phytochemical screening of ethanol extracts (12). Beyond their direct ROS-scavenging ability, flavonoids from winged bean exert potent anti-inflammatory effects that are highly relevant to human pathophysiology. In vitro studies using lipopolysaccharide (LPS)-stimulated RAW264.7 macrophages a standard model for human inflammatory responses have demonstrated that both maceration and ultrasound-assisted extracts of P. tetragonolobus can significantly suppress the production of nitric oxide (NO) and pro-inflammatory cytokines like TNF-α and IL-6 (16). This dual functionality positions winged bean flavonoids as multi-target agents against complex, inflammation-driven conditions prevalent in human populations, including metabolic syndrome, arthritis and cardiovascular disease.

2.3 Saponins
Saponins are concentrated primarily in the seeds of the winged bean (10). These amphiphilic glycosides are characterized by their ability to form stable foams and their membrane-permeabilizing properties. On one hand, they can act as anti-nutritional factors by forming insoluble complexes with cholesterol and dietary proteins, potentially impairing their digestion and absorption in the human gut (5). On the other hand, this same property is being explored for its potential to lower serum cholesterol levels and enhance the bioavailability of co-administered drugs, a concept known as phytosomal delivery (1). Furthermore, their natural role in plant defence translates to antimicrobial activity, which has been leveraged in studies showing efficacy in protecting stored legumes from pest infestation, suggesting potential applications in food preservation (10).

2.4 Terpenoids
Terpenoids and steroids have been detected in the ethanol extracts of winged bean fruits and seeds(12). While a comprehensive profile of specific terpenoid classes (e.g., triterpenes, diterpenes) in P. tetragonolobus is still an area of active research, their general presence is significant. Terpenoids are a vast class of compounds known for diverse pharmacological actions in humans, including anti-inflammatory, cytotoxic and hepatoprotective activities (5). Their

contribution to the overall bioactivity of the winged bean, particularly in modulating inflammatory pathways alongside flavonoids, is a plausible and important area for future investigation.

2.5 Lectins

Lectins, which are carbohydrate binding proteins common to legumes, are present in winged bean seeds (4). In humans, lectins can exhibit a double-edged nature. They may act as anti-nutritional factors by binding to the epithelial lining of the gut, potentially interfering with nutrient absorption and causing digestive discomfort (2). However, certain lectins also possess immunomodulatory properties that could be harnessed for therapeutic purposes, such as in targeted drug delivery or immune system regulation (5). Critically, the negative effects of lectins are largely mitigated by conventional food processing; they are heat-labile proteins that are denatured and inactivated by cooking, a standard practice for preparing winged bean seeds for human consumption (4).

2.6 Bioactive Peptides and Stilbenoids

Profound pharmaceutical interest is the emerging evidence linking winged bean to antidiabetic activity, which strongly suggests the involvement of stilbenoid like compounds. The antidiabetic activity observed in winged bean may arise from phenolic derivatives and other stilbenoid like compounds. Although pterostilbene has not been isolated from P. tetragonolobus, structurally related phenolics may contribute to these biological activities (14). A recent, high-impact study explicitly investigated the modulatory effects of winged bean bioactive on human glycemic control, demonstrating their ability to inhibit key carbohydrate-digesting enzymes like α-amylase and α-glucosidase in the human digestive tract, thereby reducing post-prandial blood glucose spikes (15). This mechanism is a hallmark of many natural antidiabetic agents. The rich phenolic backbone of the plant provides the necessary biosynthetic precursors for stilbenoids, making the search for pterostilbene or its functional analogs in winged bean a compelling research avenue with direct implications for managing type 2 diabetes in human populations.

2.7 Fatty Acids

The lipid fraction of winged bean seeds enhances its nutritional and functional profile for human consumption. The seed oil contains a favorable balance of unsaturated fatty acids, contributing to its energy density and providing essential lipids crucial for human cell membrane integrity, hormone synthesis and brain health (1). While a detailed, genotype-specific fatty acid profile is still being mapped, the presence of these healthy fats complements its high protein content, positioning the seed as a nutritionally complete food source (20).

2.8 Anti-nutritional Factors

The phytochemical matrix of the winged bean also includes anti-nutritional factors such as phytic acid (phytate), tannins and trypsin inhibitors, primarily localized in the seeds (4). Phytic acid is a strong chelator of divalent cations like iron and zinc, which can reduce their bioavailability in the human diet, a concern in populations at risk of micronutrient deficiencies (2). Tannins can bind to proteins, reducing their digestibility, while trypsin inhibitors can interfere with protein metabolism by inhibiting key digestive enzymes (5). However, it is crucial to understand that these compounds are not static liabilities. Many also possess intrinsic antioxidant properties. More importantly, modern and traditional food processing methods soaking, germination, fermentation and cooking are highly effective in degrading these anti-nutrients. For example, thermal processing denatures heat-labile trypsin inhibitors, while fermentation can significantly reduce phytate levels through enzymatic phytase activity (4). The localization of major bioactive compounds across different edible plant parts is illustrated in Figure 2.

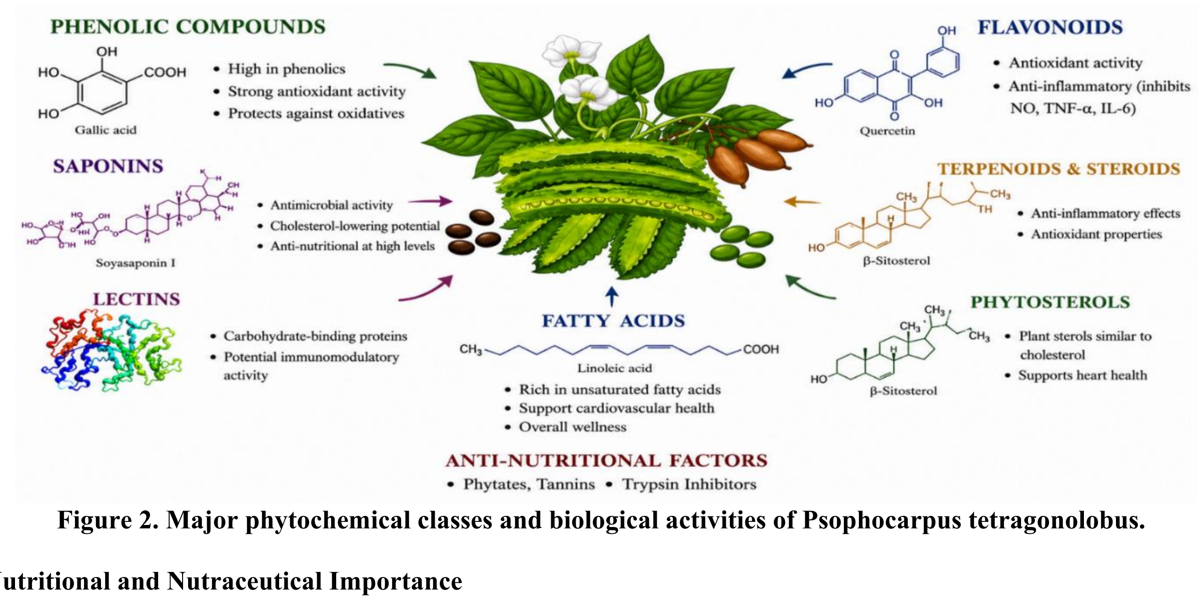

Figure 2. Major phytochemical classes and biological activities of Psophocarpus tetragonolobus.

3. Nutritional and Nutraceutical Importance

The winged bean (Psophocarpus tetragonolobus (L.) DC.) stands as a nutritional powerhouse among underutilized legumes, offering a compelling profile of macronutrients, micronutrients and bioactive compounds that confer significant functional food and nutraceutical value for human health. Its comprehensive nutritional composition, often rivalling or surpassing that of the benchmark soybean, positions it as a critical resource for addressing global malnutrition and developing novel health-promoting products.

3.1 Macronutrients

The macronutrient profile of the winged bean is its most celebrated attribute, particularly in its mature seeds. The protein content is exceptionally high, ranging from 29% to 37% on dry weight basis, which is directly comparable to soybean and significantly higher than most other legumes like common beans or lentils (4, 6). This protein is not only plentiful but of high quality because it has all nine essential amino acids needed by humans, especially lysine, which is a limiting amino acid in many cereals, as well as Sulphur containing amino acids such as methionine and cysteine, which are often lacking in most legumes. This makes the protein in the winged beans very complete and thus a great food for complementing the protein content of cereals. The seeds have good amounts of fiber (about 16-25%) and a good lipid profile (13-20%) (6). The seed oil is rich in unsaturated fatty acids, contributing to its energy density and providing essential lipids crucial for human cell membrane integrity and metabolic functions 2. The carbohydrate content, while present, is moderate, making the seed a nutrient-dense, low glycemic index food option.

3.2 Micronutrients

Beyond macronutrients, the winged bean is a rich repository of essential vitamins and minerals vital for human physiological functions as given in (Figure 3). The seeds are a good source of B-complex vitamins, including thiamine (B1), riboflavin (B2) and niacin (B3) (6). The green pods and leaves are particularly rich in vitamin C (ascorbic acid) and provitamin A (beta-carotene), nutrients critical for immune function, collagen synthesis and vision, respectively. In terms of minerals, the plant provides significant amounts of calcium, phosphorus, iron and zinc (4). Calcium and phosphorus are fundamental for good bone health, while iron is essential for oxygen transport in hemoglobin and zinc plays a key role in immune function and enzymatic reactions. However, the bioavailability of these minerals can be influenced by the presence of anti-nutritional factors like phytic acid, which chelates divalent cations such as iron and zinc, potentially reducing their absorption in the human gut. This highlights the importance of appropriate food processing to optimize mineral bioavailability.

Macronutrients			Vitamins			Minerals			Other nutrients		
Nutrient	Value	% RDA	Nutrient	Value	% RDA	Nutrient	Value	% RDA	Nutrient	Value	% RDA
Energy	49 Kcal	2.5%	Vitamin A	128 IU	4%	Potassium (K)	240 mg	5%	Sodium (Na)	4 mg	<1%
Carbohydrates	4.31 g	3%	Vitamin C	18.3 mg	30%	Calcium (Ca)	84 mg	8%	Dietary Fiber*	–	Not established
Protein	6.95 g	12%	Thiamin (B_1)	0.140 mg	12%	Magnesium (Mg)	34 mg	8%			
Total fat	0.87 g	3%	Riboflavin (B_2)	0.100 mg	8%	Phosphorus (P)	37 mg	5%			
Cholesterol	0 mg	0%	Niacin (B_3)	0.900 mg	6%	Iron (Fe)	1.5 mg	19%			
			Pyridoxine (B_6)	0.113 mg	9%	Zinc (Zn)	0.39 mg	3%			
			Folate	66 µg	16.5%	Manganese (Mn)	0.218 mg	9%			
			Pantothenic acid (B_5)	0.059 mg	1%	Copper (Cu)	0.051 µg	5.5%			
						Selenium (Se)	1.5 µg	3%			

Figure 3. Nutritional profile of winged bean (Psophocarpus tetragonolobus) per 100 g edible portion. (Source: USDA National Nutrient Database)

3.3 Functional Food Value

The concept of a functional food providing health benefits beyond basic nutrition is epitomized by the winged bean. Its value stems from the synergistic interplay between its high-quality macronutrients and its dense matrix of phytochemicals. The high dietary fiber content promotes digestive health, increases satiety and aids in the regulation of blood glucose and cholesterol levels. (9). The rich array of phenolic compounds and flavonoids imparts potent antioxidant activity, which helps protect the body's cells from oxidative damage caused by free radicals, a process implicated in aging and chronic diseases like cardiovascular disease and cancer (12, 16). Furthermore, its documented anti-inflammatory properties, mediated through the suppression of pro-inflammatory cytokines, add another layer of functional benefit, as chronic inflammation is a root cause of many modern non-communicable diseases (16). The combination of high-quality protein, healthy fats, fiber and bioactive antioxidants makes every edible part of the winged bean from young pods consumed as a vegetable to mature seeds used as a protein supplement a natural functional food.

3.4 Nutraceutical Potential

The nutraceutical potential of the winged bean, the use of its isolated components or extracts as health-promoting agents or therapeutic adjuvants is a rapidly growing area of research. Its extracts have demonstrated significant antidiabetic activity by inhibiting key enzymes like α-amylase and α-glucosidase, which slows carbohydrate digestion and reduces post-prandial blood glucose spikes, a mechanism highly relevant for managing type 2 diabetes (15). The saponins present in the seeds have shown antimicrobial and insecticidal properties, suggesting applications not only in food preservation but also as natural biocontrol agents (10). The plant's ability to modulate inflammatory pathways in human-relevant cellular models points to its potential in developing natural anti-inflammatory supplements (16). Moreover, the anticipated presence of phytosterols offers a pathway for cholesterol-lowering nutraceuticals, as these compounds compete with dietary cholesterol for absorption in the gut. The recent completion of its high-quality genome assembly provides a powerful tool to identify the specific genes responsible for the biosynthesis of these valuable compounds, paving the way for targeted breeding or biotechnological production of standardized nutraceutical extracts (7, 17).

4. Pharmacological Activities

The pharmacological activities of Psophocarpus tetragonolobus (L.) DC., commonly known as winged bean, are a direct manifestation of its rich and diverse phytochemical composition, which confers a broad spectrum of health benefits with significant relevance to human physiology and disease management. This section provides a concise yet comprehensive overview of its key pharmacological properties, emphasizing mechanisms of action, plant-part specificity and evidence from human-relevant models.

4.1 Antioxidant Activity

The antioxidant capacity of winged bean is its most robustly documented property, serving as a primary defense against oxidative stress a key pathological driver in chronic human diseases like cardiovascular disorders, neurodegeneration and cancer. This activity has been validated through multiple standard in vitro assays. The DPPH (1,1-diphenyl-2-picrylhydrazyl) radical scavenging assay demonstrates that ethanol extracts of winged bean fruit exhibit potent, dose-dependent activity, with efficacy increasing at concentrations of 10, 50, 100 and 150 ppm (12). Similarly, the ABTS (2,2'-azino-bis (3-ethylbenzothiazoline-6-sulfonic acid)) assay confirms high free radical quenching power, while the FRAP (Ferric Reducing Antioxidant Power) assay shows a strong ability to reduce ferric ions, indicating electron-donating potential (13). The primary mechanism is attributed to its dense matrix of phenolic compounds, particularly flavonoids and tannins, which neutralize reactive oxygen species (ROS) by donating hydrogen atoms or electrons, thereby preventing oxidative damage to cellular macromolecules (6). The antioxidant activity of Psophocarpus tetragonolobus has been evaluated using various in vitro assays, with phenolic compounds and flavonoids identified as the principal contributors to its free radical scavenging capacity. A summary of representative antioxidant studies is presented in Table 2.

Table 2. Summary of antioxidant activity of Psophocarpus tetragonolobus.

Plant part	Major bioactive compounds	Antioxidant assay	Reported activity	Reference
Seeds	Phenolic compounds, flavonoids, tannins	DPPH, TEAC	Strong antioxidant activity was demonstrated through efficient free radical scavenging, with activity positively associated with total phenolic and flavonoid contents.	(4)
Seeds	Phenolic compounds	DPPH, FRAP, TEAC, CUPRAC	Significant antioxidant capacity among different genotypes; high-antioxidant genotypes identified	(13)
Leaves	Gallic acid, caffeic acid, chlorogenic acid, ferulic acid, quercetin, rutin, kaempferol	HPLC-based phytochemical profiling	High accumulation of antioxidant phytochemicals contributing to antioxidant potential	(4)
Young pods	Phenolic compounds, flavonoids	DPPH	High phenolic content associated with strong radical scavenging activity	(6)
Fruits	Phenolics and flavonoids	DPPH	Dose-dependent antioxidant activity in ethanolic extracts	(12)
Different plant parts	Phenolics and flavonoids	Total phenolic content (TPC), Total flavonoid content (TFC)	Antioxidant activity strongly correlated with phenolic composition across plant tissues	(6)

4.2 Anti-inflammatory Activity

Winged bean exhibits significant anti-inflammatory effects, highly relevant for managing chronic inflammatory conditions such as arthritis and metabolic syndrome. Using LPS-stimulated RAW264.7 murine macrophages a well-established model for human innate immune responses studies shows that both maceration and ultrasound-assisted extracts significantly suppress the production of key inflammatory mediators (16). Specifically, these extracts inhibit the release of nitric oxide (NO) and downregulate the secretion of pro-inflammatory cytokines, most notably tumor necrosis factor-alpha (TNF-α) and interleukin-6 (IL-6) (16). While direct COX enzyme inhibition data is limited, the suppression of the NF-κB (nuclear factor kappa-light-chain-enhancer of activated B cells) signaling pathway is a central plausible mechanism. NF-κB is a master regulator of inflammatory gene expression and the phenolic constituents of winged bean are known to interfere with its activation, providing a broad-spectrum anti-inflammatory effect (5).

4.3 Antimicrobial Activity

The winged bean exhibits notable antimicrobial properties, consistent with its traditional use in food preservation. Its saponin-rich seed extracts have been shown to effectively protect stored cowpea seeds from Callosobruchus maculatus (bruchid beetle) infestation, highlighting its natural pesticidal activity (10). Phytochemical screening confirms the presence of saponins, flavonoids and tannins, all of which are well-established antimicrobial agents (11). Mechanistically, saponins disrupt microbial cell membranes due to their amphiphilic surfactant-like nature, leading to leakage of intracellular contents and eventual cell death. Tannins exert antimicrobial action by binding to microbial enzymes and adhesins, thereby inactivating essential proteins and preventing colonization. Flavonoids contribute by interfering with nucleic acid synthesis and microbial energy metabolism, while also generating oxidative stress within microbial cells.
Although systematic studies against a wide panel of pathogens are still limited, preliminary evidence supports activity against Gram-positive bacteria (e.g., Staphylococcus aureus), Gram-negative bacteria (e.g., Escherichia coli) and fungi (e.g., Candida albicans). The existing data strongly support winged bean as a promising source of natural antimicrobial agents for nutraceutical and pharmaceutical applications (5). Future research should focus on compound isolation, MIC determination and synergy testing with conventional antibiotics to validate its therapeutic potential.

4.4 Antidiabetic Activity

One of the most promising pharmacological activities of winged bean is its antidiabetic potential. A recent high-impact study explicitly investigated the modulatory effects of its bioactive compounds on human glycemic control (15). The research demonstrated that winged bean extracts can effectively inhibit two key carbohydrate-digesting enzymes in the small intestine: α-amylase and α-glucosidase. By inhibiting these enzymes, the breakdown of complex carbohydrates into simple sugars is slowed, leading to a reduction in post-prandial blood glucose spikes a critical therapeutic goal in managing type 2 diabetes mellitus. This mechanism suggests the presence of specific bioactive molecules, potentially stilbenoid analogs or other phenolic derivatives, that interact with the active sites of these enzymes (15).

4.5 Anticancer Activity

While direct in-depth studies on anticancer activity are still emerging, the plant's rich phytochemical profile provides a strong mechanistic rationale. Many of its constituent compounds, including specific flavonoids and phenolic acids, are known to induce apoptosis (programmed cell death) in various cancer cell lines through the activation of caspase enzymes, the executioners of the apoptotic pathway (6). The flavonoids (quercetin, kaempferol) and phenolic acids (caffeic, ferulic) are the most directly associated with apoptosis and cell cycle arrest, while saponins and phytosterols contribute to membrane disruption and cholesterol modulation, indirectly supporting anticancer effects. Lectins may have immunomodulatory potential but require controlled processing to avoid toxicity. Furthermore, these compounds can induce cell cycle arrest, halting the uncontrolled proliferation of malignant cells at specific checkpoints (e.g., G1/S or G2/M phase) (1). The potent antioxidant activity also contributes indirectly by mitigating DNA damage from oxidative stress, a known initiator of carcinogenesis (6).

4.6 Cardioprotective Activity

The cardioprotective potential of winged bean is inferred from several established properties. Its seed oil is rich in unsaturated fatty acids, contributing to a favorable lipid profile beneficial for cardiovascular health (4). The anticipated presence of phytosterols offers a direct mechanism for cholesterol lowering, as these plant sterols compete with dietary cholesterol for absorption in the gut, thereby reducing serum LDL ("bad") cholesterol levels (1). Furthermore, its potent antioxidant and anti-inflammatory activities help protect the vascular endothelium from oxidative damage and chronic inflammation, two key processes in the development of atherosclerosis (5).

Table 3. Pharmaceutical and nutraceutical applications

Application Area	Component Used	Rationale	Development Stage
Nutraceutical Supplements	Defatted seed flour, protein isolate	High-quality plant protein and essential amino acids	Commercially viable; Similar to soy (1, 21)
Antioxidant Formulations	Phenolic extracts, tocopherol-rich oil	Natural alternative to synthetic antioxidants (e.g., BHT)	Demonstrated in vitro efficacy (16, 22)
Functional Food	Protein isolates, fiber-rich	Emulsification, gelation,	Functional properties

Ingredients	fractions	satiety enhancement	well-characterized (21)
Dermatological Products	Seed oil (tocopherols, phytosterols)	Skin barrier repair, anti-aging, acne treatment	Supported by antibacterial and antioxidant data (22, 23)
Drug Delivery Systems	Protein nanoparticles/hydrogels	Biocompatible carriers for controlled release	Demonstrated feasibility via protein functionalization (1, 24)
Menopausal Health Supplements	Phytosterol-rich seed oil	Natural alternative to hormone therapy	Extraction optimized via supercritical CO_2 (22)

5. Pharmaceutical Applications

The winged bean represents a compelling yet underutilized resource for pharmaceutical innovation, offering a rich reservoir of bioactive compounds with significant potential in drug discovery, formulation science and as therapeutic agents themselves. Its diverse phytochemical profile, encompassing proteins, peptides, polyphenols, lipids and specialized metabolites, positions it as a multifaceted candidate for modern pharmaceutical applications.

5.1 Natural Drug Discovery

In the realm of natural drug discovery, the rationale for investigating winged bean is firmly grounded in its chemical composition. The plant is a known source of phenolic compounds (including flavonoids and phenolic acids), tocopherols, phytosterols and a high concentration of seed storage proteins that can be hydrolyzed into bioactive peptides (6, 11, 15). These chemical classes are frequently associated with a range of biological activities, including antioxidant, anti-inflammatory, antimicrobial and enzyme-modulatory effects. Research has confirmed the substantial antioxidant capacity of various winged bean genotypes, which is directly correlated with their total phenolic content (13, 25). This provides a strong foundation for a discovery pipeline based on bioassay-guided fractionation, where extracts from seeds, leaves or tubers could be screened against specific targets such as oxidative stress pathways, inflammatory mediators like COX/LOX enzymes, or key metabolic enzymes involved in diabetes (16).

5.2 Potential Pharmaceutical Lead Compounds

From this phytochemical complexity, several promising pharmaceutical lead molecules can be identified. The polyphenolic fraction, particularly flavonoid glycosides and derivatives of ferulic or caffeic acid, serves as a source of redox modulators and potential enzyme inhibitors (15). The lipid-soluble fraction of winged bean seed oil is notably rich in unsaturated fatty acids and vitamin E homologs (tocopherols), alongside phytosterols (22). These components are strong candidates for dermatological formulations, where tocopherols act as chain-breaking antioxidants to protect skin lipids and phytosterols can support skin barrier repair and offer cholesterol-lowering benefits in nutraceutical contexts (22).

Furthermore, the plant produces specialized proteins like trypsin/chymotrypsin inhibitors, which have demonstrated bio-pesticidal activity by affecting insect growth (26). While their direct therapeutic use requires careful safety profiling because of potential immunogenicity, they provide valuable structural templates for developing protease-modulating drugs for conditions such as cancer or viral infections. Enzymatic hydrolysis of the abundant seed protein (which can exceed 30% of dry weight) is a proven method to generate bioactive peptides with documented angiotensin-I-converting enzyme (ACE) inhibitory and antioxidant properties, suggesting applications in managing hypertension and oxidative stress-related disorders (24, 27, 28).

5.3 Drug Formulation Potential

The inherent bioactivity of winged bean translates directly into significant drug formulation potential. The tocopherol-rich oil fractions can serve as natural antioxidant excipients, stabilizing oxidation-sensitive active pharmaceutical ingredients (APIs) in lipid-based formulations such as emulsions or Self-microemulsifying drug delivery systems (SMEDDS), thereby extending product shelf life (22). Similarly, seed protein isolates, which exhibit functional properties such as gelation and emulsification comparable to soy protein (21), can be engineered into advanced delivery systems. They can form nanoparticles, hydrogels or films capable of encapsulating bioactive compounds such as polyphenols or poorly water-soluble drugs to improve chemical stability, bioavailability and controlled drug release (29). The protein and phospholipid components also possess natural surfactant properties that enhance the dispersion and stability of hydrophobic compounds in oral supplements and nutraceutical formulations.

5.4 Pharmaceutical Excipients

Winged bean components also show considerable promise as pharmaceutical excipients. Defatted flour or purified protein isolates can function as binders or fillers in tablet formulations, whereas protein-polysaccharide composites may be developed as film-forming materials for enteric or sustained-release coatings (6).

Likewise, the seed oil, with its high triacylglycerol content, represents a suitable natural lipid vehicle for soft gel capsules and other lipid-based drug delivery systems (LBDDS). However, successful pharmaceutical application requires stringent quality control to ensure minimal microbial contamination, reduced mycotoxin burden, effective removal of antinutritional factors such as lectins and trypsin inhibitors through validated processing techniques and comprehensive allergenicity assessment (18, 30).

5.5 Bioactive Protein Isolates

Protein isolates constitute one of the most valuable pharmaceutical components of winged bean. Their dominant globulin structure provides the functional basis for developing advanced drug delivery vehicles (21). Beyond their structural role, these proteins are important because they serve as precursors for bioactive peptides. Studies employing alkalise hydrolysis have produced peptide fractions exhibiting strong DPPH and ABTS radical scavenging activities, thereby confirming their antioxidant potential (24). Future peptidomics-guided fractionation combined with quantitative structure-activity relationship (QSAR) modelling could accelerate identification of peptide sequences responsible for ACE inhibition or antimicrobial activity, facilitating their development as nutraceuticals or novel therapeutic agents.

5.6 Plant Derived Therapeutics

Winged bean also represents a promising source of plant-derived therapeutics. Standardized extracts enriched with phenolic compounds and tocopherols could be developed as adjunctive therapies or cosmeceuticals for diseases associated with oxidative stress and chronic inflammation, including metabolic syndrome and skin photodamage (16). The phytosterol-rich oil fraction also offers potential for supporting cardiovascular health through cholesterol management. Preliminary studies have suggested broader pharmacological applications; for example, leaf infusions have shown efficacy in rat malaria models (19), while fruit extracts demonstrated antibacterial activity against Propionibacterium acnes, indicating possible applications in infectious disease management.

Nevertheless, future therapeutic development requires comprehensive safety evaluation, pharmacokinetic studies and toxicity profiling before clinical application.

5.7 Pharmaceutical Biotechnology

Pharmaceutical biotechnology offers powerful opportunities to maximize the medicinal potential of winged bean. Controlled bioprocessing methods such as sprouting or fermentation using GRAS (Generally Recognized as Safe) microorganisms can enrich free phenolics while reducing antinutritional proteins, thereby producing extracts with improved biological activity (1). Advanced extraction technologies, including supercritical CO_2 extraction, have already been optimized for winged bean seed oil, enabling efficient recovery of oleic acid-rich oil together with valuable unsaponifiable constituents such as tocopherols and phytosterols.

Furthermore, the recent development of genomic resources and genetic linkage maps for winged bean provides opportunities for future metabolic engineering and marker-assisted breeding to develop cultivars enriched in pharmaceutically valuable compounds. These advances could transform this underutilized crop into a sustainable source of plant-derived pharmaceuticals.

6. Bioavailability and Pharmacokinetics

The bioavailability and pharmacokinetic profile of phytochemicals derived from Psophocarpus tetragonolobus (winged bean) are critical determinants of their therapeutic efficacy. Although winged bean is a rich source of proteins, unsaturated fats, dietary fiber and bioactive phytochemicals, including polyphenols, saponins and phytosterols, the clinical effectiveness of these compounds depends on their absorption, distribution, metabolism and excretion (ADME) following oral administration (31). The absorption of winged bean bioactive compounds is influenced by several intrinsic factors. Naturally occurring trypsin and chymotrypsin inhibitors reduce protein digestibility and amino acid bioavailability (32, 33). Similarly, polyphenols exhibit low membrane permeability and may interact with proteins and dietary fibre, reducing their intestinal absorption (34). Lipophilic compounds such as phytosterols and certain saponins also exhibit poor water solubility and require micellar solubilization for efficient absorption. Following absorption, polyphenols are extensively metabolized in the liver and circulate mainly as conjugated metabolites, while many saponins and high-molecular-weight polyphenols primarily exert local effects within the gastrointestinal tract(35). Extensive first-pass metabolism further limits the systemic availability of winged bean phytochemicals. Polyphenols undergo glucuronidation, sulphation and methylation, producing metabolites that often differ in biological activity from their parent compounds (36). In addition, antinutritional factors such as phytate reduce the bioavailability of essential minerals, including iron and zinc, through mineral chelation, although animal studies have reported relatively high zinc bioavailability under controlled experimental conditions (37, 38). Several approaches have been investigated to improve bioavailability. Conventional processing methods, including boiling, autoclaving, fermentation and germination, effectively reduce heat-labile antinutritional factors such as trypsin inhibitors and lectins, thereby improving protein digestibility and mineral availability (39). In addition, advanced delivery systems such as liposomes, phytosomes, solid lipid nanoparticles (SLNs), nanostructured lipid carriers (NLCs) and microencapsulation have shown considerable potential for improving the stability, solubility and gastrointestinal absorption of poorly bioavailable phytochemicals while protecting them from degradation during digestion (40).

Overall, improving the bioavailability of winged bean phytochemicals remains essential for their successful pharmaceutical and nutraceutical application. Future research should focus on integrating optimized processing techniques with advanced delivery systems to enhance therapeutic efficacy and facilitate the clinical translation of this promising underutilized legume (40).

7. CONCLUSION

Psophocarpus tetragonolobus (winged bean) is an underutilized tropical legume with exceptional nutritional value and significant pharmaceutical and nutraceutical potential. Current scientific evidence demonstrates that its seeds, pods, leaves, flowers and tubers contain a diverse array of bioactive phytochemicals, including phenolic compounds, flavonoids, saponins, terpenoids, bioactive peptides and phytosterols, which collectively contribute to its antioxidant, anti-inflammatory, antimicrobial, antidiabetic, cardioprotective and potential anticancer effects. These biological properties highlight winged bean as a promising natural source for the development of functional foods, nutraceuticals and plant-derived therapeutic agents. Recent advances in phytochemical characterization, extraction technologies and genomic research have further strengthened the scientific basis for exploring this crop as a valuable pharmaceutical resource. In addition, its high-quality proteins, bioactive peptides and seed oil possess favorable physicochemical properties that support potential applications in drug delivery systems, pharmaceutical excipients and advanced formulation strategies. Despite these promising findings, most pharmacological evidence remains limited to in vitro studies and experimental animal models. Comprehensive toxicological assessments, pharmacokinetic and pharmacodynamic investigations, standardized extraction and characterization of bioactive constituents and well-designed clinical trials are essential to establish the efficacy, safety and therapeutic applicability of winged bean in humans.

Overall, P. tetragonolobus represents a sustainable and multifunctional medicinal plant with considerable potential to bridge nutritional science and pharmaceutical research. Future multidisciplinary studies integrating phytochemistry, molecular pharmacology, biotechnology and clinical validation will be crucial for identifying bioactive lead compounds, elucidating their mechanisms of action and translating this underutilized crop into evidence-based pharmaceutical and nutraceutical products. Such efforts will not only enhance the medicinal and commercial value of P. tetragonolobus but also contribute to the development of sustainable therapeutics, improved public health and global food security

Acknowledgments

The authors express their sincerely acknowledgement for the academic support and institutional facilities provided by the Department of Postharvest Management, Horticultural College & Research Institute, Tamil Nadu Agricultural University (TNAU), Coimbatore, which enabled the successful completion of this review work. The authors are grateful to the faculty members and research colleagues for their valuable suggestions, constructive comments and continuous encouragement throughout the preparation of this manuscript. The authors also appreciate the university library and access to online scientific databases that facilitated an extensive and comprehensive literature survey.

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Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this review article.

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