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Phytomedicinal and nutritional dynamics of pulses: Linking antioxidant potential with health benefits

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Abstract

Pulses, the edible seeds of leguminous plants, have long been integral to global food and nutritional security due to their exceptional nutrient density and environmental sustainability. Beyond their traditional dietary role, pulses are increasingly recognized as potent sources of bioactive compounds that contribute to human health and disease prevention. This review comprehensively examines the phytomedicinal and nutritional dynamics of major pulses, emphasizing their antioxidant potential and associated health benefits. Pulses are rich in high-quality proteins, complex carbohydrates, dietary fiber, essential vitamins and minerals, while also containing diverse secondary metabolites such as phenolics, flavonoids, saponins, phytosterols, carotenoids and tocopherols. These phytochemicals exert strong antioxidant activity through mechanisms including free radical scavenging, metal ion chelation, lipid peroxidation inhibition and modulation of endogenous antioxidant enzymes. The synergistic interaction of these compounds supports a broad range of pharmacological effects antidiabetic, antihyperlipidemic, anti-inflammatory, anticancer and hepatoprotective positioning pulses as functional foods and nutraceutical ingredients. The review also explores the influence of traditional and modern processing methods soaking, germination, fermentation, extrusion, microwave and enzyme-assisted treatments on the bioavailability and retention of nutrients and bioactives. While processing improves digestibility and reduces antinutritional factors, emerging green technologies have been shown to enhance the stability and efficacy of antioxidant compounds. Despite significant progress, challenges remain in terms of nutrient bioavailability, sensory acceptability, technological scalability and limited clinical validation of health effects. Addressing these gaps through molecular breeding, advanced food processing and clinical research will be key to unlocking the full potential of pulses. In the context of climate change and rising chronic disease burdens, pulses offer a sustainable, affordable and health-promoting solution for future global nutrition.

1. Introduction

Pulses, the dry edible seeds of leguminous plants belonging to the family Fabaceae, hold a central position in global food systems due to their remarkable nutritional quality and environmental sustainability. They are cultivated in diverse agroecological regions and form a staple component of diets in Asia, Africa and Latin America (Chiorcea Paquim *et al*., 2020). Globally, pulses contribute significantly to food and nutritional security because of their high protein content, complex carbohydrates, dietary fiber, vitamins and minerals. In low- and middle-income countries, pulses serve as an affordable and accessible source of dietary protein, often referred to as the “poor man’s meat” due to their ability to supplement cereal-based diets and provide essential amino acids. Their balanced amino acid composition, particularly rich in lysine, complements the methionine-rich profile of cereals, forming a nutritionally complete combination that enhances overall protein quality (Ciudad-Mulero *et al*., 2020). From an agroecological perspective, pulses play a vital role in promoting sustainable agriculture. Through their symbiotic association with *Rhizobium* species, they fix atmospheric nitrogen, thereby improving soil fertility and reducing the dependency on synthetic nitrogen fertilizers. This natural nitrogen-fixing ability contributes to soil health restoration, energy conservation and reduced greenhouse gas emissions (FAO, 2024). Additionally, their inclusion in crop rotation and intercropping systems enhances biodiversity, disrupts pest and disease cycles and promotes long-term sustainability in farming. Such ecological benefits have positioned pulses as key contributors to climate-resilient agriculture and global sustainability goals.

Beyond their nutritional and environmental significance, pulses are increasingly recognized for their phytochemical richness and health-promoting properties. They contain a wide array of bioactive compounds, including phenolic acids, flavonoids, tannins, saponins and phytosterols, which exhibit potent antioxidant, anti-inflammatory and antimicrobial activities. These phytochemicals neutralize reactive oxygen species (ROS) and reduce oxidative stressa key factor implicated in the pathogenesis of chronic diseases such as diabetes, cardiovascular disorders, cancer and neurodegenerative conditions. Recent studies have demonstrated that the regular consumption of pulses is associated with improved glycemic control, lipid metabolism and cardiovascular function (Bibi *et al*., 2024). The

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concept of pulses as functional foods and nutraceutical ingredients has gained significant momentum in recent years. Functional foods derived from pulses not only provide essential nutrients but also deliver specific physiological benefits that contribute to disease prevention and overall well-being. A recent dietary survey in the United Kingdom found that pulse-based foods enhanced micronutrient intake and improved serum micronutrient status among children and adolescents. Likewise, a comparative analysis of food sustainability metrics ranked pulses as one of the most nutrient-dense and environmentally sustainable protein sources, outperforming most animal-based foods (Thenuwara *et al*., 2024)

Despite their well-established nutritional importance, the phytomedicinal and antioxidant potential of pulses remains insufficiently explored. Differences in cultivar, growing environment and postharvest processing significantly affect the concentration and bioavailability of bioactive compounds. Furthermore, while individual studies have documented the antioxidant or antidiabetic potential of specific pulse species, comprehensive reviews linking nutritional dynamics, phytochemical profiles and health benefits are still limited. Hence, this review aims to provide an integrative understanding of the phytomedicinal and nutritional dynamics of pulses, emphasizing their role as natural antioxidants and health-enhancing foods. The specific objectives are:

- To explore the compositional diversity of pulses in terms of macronutrients, micronutrients and bioactive phytochemicals.
- To elucidate the mechanisms underlying their antioxidant activities and their roles in mitigating oxidative stress.
- To establish connections between the nutritional and phytochemical components of pulses and their health-promoting and disease-preventive effects.

By consolidating recent advances, this review highlights the dual importance of pulses as both a nutrient-dense food source and a phytomedicinal reservoir, underscoring their contribution to global nutritional security, sustainable agriculture and the prevention of chronic diseases. Their diverse bioactive profiles and antioxidant potential place pulses at the forefront of modern health-oriented and eco-friendly food systems.

2. Nutritional composition of pulses

2.1 Macronutrient profile

2.1.1 Protein content and amino acid balance

Pulses are excellent plant-based sources of dietary protein, typically containing between 20% and 30% protein by dry weight. The major protein fractions are globulins and albumins, which contribute to their nutritional and functional properties in food systems. Although, pulse proteins are relatively low in sulfur-containing amino acids such as methionine and cysteine, they are rich in lysine, which complements the amino acid profile of cereals. This makes pulse–cereal combinations nutritionally complete and highly beneficial in vegetarian and plant-based diets. Protein digestibility and amino acid availability in pulses are influenced by processing methods such as cooking, soaking, fermentation and germination. These techniques reduce antinutritional factors, such as trypsin inhibitors and tannins, thereby improving overall protein utilization (Timilsena *et al*., 2023). Processed pulses show improved digestibility and higher values of protein quality indices such as the protein digestibility corrected amino acid score (PDCAAS) and the digestible indispensable amino acid score (DIAAS). This highlights their potential as sustainable alternatives to animal proteins in human nutrition (Figure 1).

2.1.2 Complex carbohydrates, dietary fiber and resistant starch

Carbohydrates form the major component of pulses, constituting about 55-65% of their dry weight. Pulse starch has a higher proportion of amylose than amylopectin, which contributes to a lower glycemic index and slower digestion compared to cereal starches. This property is particularly beneficial for individuals with metabolic disorders such as diabetes. Pulses are also rich in dietary fiber, typically contributing 10-20% of dry weight. The fiber fraction includes both soluble and insoluble typessuch as pectin, hemicellulose and cellulosethat promote digestive health, regulate blood glucose levels and aid cholesterol metabolism. In addition, pulses contain resistant starch, which functions as a prebiotic by promoting the growth of beneficial gut bacteria and supporting the production of short-chain fatty acids that enhance intestinal health (Langyan *et al*., 2022).

2.1.3 Fatty acid composition and lipid fraction

Pulses are naturally low in fat, containing only about 1-5% lipids, yet the quality of their fat composition is nutritionally valuable. The lipid fraction is dominated by unsaturated fatty acids, particularly linoleic and α-linolenic acids, which are essential for maintaining cardiovascular health. The high unsaturated-to-saturated fat ratio and the presence of sterols, phospholipids and tocopherols add to their functional and nutraceutical importance (Kumar *et al*., 2022). This makes pulses suitable for low-fat, heart-healthy diets.

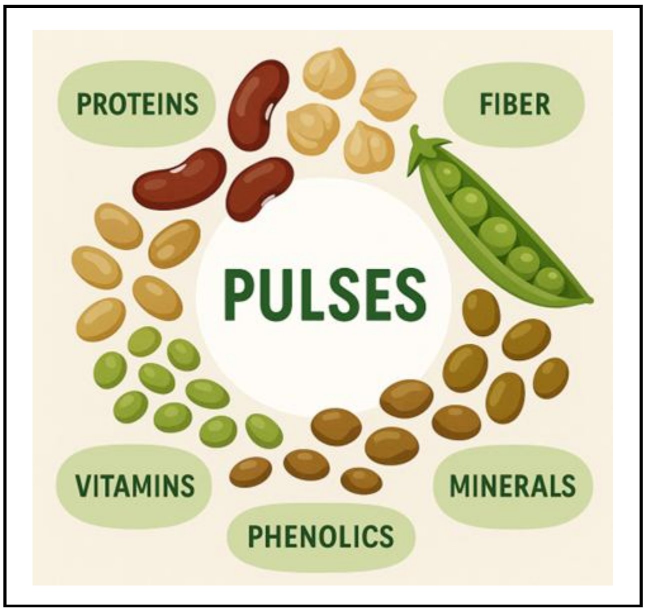

Figure 1: Nutritional and phytochemical composition of pulses.

2.2 Micronutrients

2.2.1 Vitamins: Folate, thiamine, riboflavin and niacin

Pulses are a rich source of several B-complex vitamins, especially folate (vitamin B9), which is essential for DNA synthesis and cellular metabolism. They also provide thiamine (B1), riboflavin (B2), niacin (B3) and pyridoxine (B6), all of which are crucial for energy metabolism and neural function. Germination and fermentation are known to enhance the availability of these vitamins by activating endogenous enzymes and synthesizing free vitamin forms (Begum *et al*., 2023). The inclusion of pulses in regular diets can therefore contribute significantly to the daily intake of essential vitamins and help prevent micronutrient deficiencies.

2.2.2 Minerals: Iron, zinc, magnesium, potassium and phosphorus

Pulses supply a wide range of essential minerals required for physiological and biochemical functions. They are particularly rich in iron and zinc, which are necessary for oxygen transport and immune competence, as well as magnesium and potassium, which are vital for neuromuscular and cardiovascular function. Phosphorus plays an important role in bone formation and energy metabolism. Although antinutritional factors such as phytates and tannins can reduce mineral bioavailability, their effects can be minimized through soaking, germination, fermentation and thermal processing (Hou *et al*., 2023). These methods enhance the solubility and absorption of minerals, making pulses a reliable source of essential micronutrients.

2.2.3 Bioavailability and effect of processing

Processing has a significant impact on the nutrient composition and bioavailability of pulses. Techniques such as soaking and cooking remove soluble antinutrients, while germination increases enzymatic activity and vitamin content. Fermentation, particularly with beneficial microorganisms, not only improves flavor and digestibility but also enhances mineral availability by degrading phytates. Modern approaches, including microwave-assisted and enzyme-aided processing, have further improved nutrient retention while reducing cooking time. Collectively, these processes contribute to making pulses more palatable, digestible and nutritionally efficient (Dhull *et al*., 2023).

2.3 Comparative nutritional analysis

2.3.1 Comparison with cereals and other legumes

Compared with cereals, pulses contain nearly twice the amount of protein and significantly higher levels of lysine and dietary fiber. While cereals are rich in sulfur-containing amino acids but deficient in lysine, pulses offer a complementary nutritional balance, making their combination highly effective in improving diet quality. Pulses also have a lower glycemic index than most cereals, resulting in better blood sugar control.When compared with oilseeds and other legumes such as soybeans or peanuts, pulses generally have lower fat content but comparable carbohydrate and protein levels (Benayad *et al*., 2021). Their high fiber and resistant starch content make them particularly suitable for weight management and metabolic health. Thus, pulses represent a unique category of foods that combine nutrient density with health-promoting attributes.

2.3.2 Nutritional index and protein quality (PDCAAS, DIAAS)

Protein quality is often assessed using standardized indices such as PDCAAS and DIAAS. Pulses generally score moderately on these scales due to certain amino acid limitations; however, processing and combination with cereals can elevate these scores to near-ideal levels. The complementary amino acid profiles of cereals and pulses result in a higher overall protein quality and digestibility. These attributes reaffirm the nutritional importance of pulses as integral components of balanced and sustainable diets. Overall, pulses represent an exceptional blend of macronutrients, micronutrients and bioactive compounds. Their rich nutritional composition, combined with low environmental impact and affordability, underscores their vital role in achieving food and nutritional security globally (Sahasakul *et al*., 2022).

3. Phytochemical constituents and bioactive compounds

Pulses are not only nutrient-rich but also possess an exceptional diversity of phytochemicals that impart distinct functional and medicinal properties. These bioactive molecules such as phenolic compounds, flavonoids, tannins, saponins, alkaloids, isoflavones, carotenoids, tocopherols and phytosterols serve as natural defense compounds in plants and contribute to human health by exerting antioxidant, anti-inflammatory, antidiabetic and cardioprotective effects (Ferreira *et al*., 2021). The quantity and composition of these phytochemicals vary with species, genotype, environmental conditions and postharvest processing, yet their collective influence defines the phytomedicinal potential of pulses.

3.1 Phenolic compounds

Phenolic compounds constitute the largest class of bioactive molecules in pulses. They are secondary metabolites characterized by one or more hydroxyl groups attached to an aromatic ring and are largely responsible for the antioxidant capacity of pulse seeds. Phenolic compounds are broadly categorized into phenolic acids, flavonoids and tannins. Among phenolic acids, p-coumaric, ferulic, caffeic, sinapic and gallic acids are commonly found in the seed coats of lentils, chickpeas and black grams. These compounds are known for their radical-scavenging and metal-chelating properties, which help prevent oxidative damage in biological systems. Flavonoids, another major subgroup, include flavonols (quercetin, kaempferol), flavones (luteolin, apigenin) and flavan-3-ols (catechin, epicatechin). Their antioxidant efficacy arises from their ability to donate hydrogen atoms or electrons to neutralize free radicals. In addition to antioxidant action, phenolics contribute to color, flavor and astringency in pulse-based foods (Yegrem, 2021). They also play protective roles in preventing cellular lipid peroxidation, DNA damage and inflammatory responses. Processing techniques such as germination and fermentation often increase the extractable phenolic content, as enzymatic activity during these processes releases bound phenolics from cell-wall complexes. Phenolics in pulses thus represent a critical interface between nutrition and medicine, linking diet to disease prevention.

3.2 Alkaloids, saponins and tannins

Alkaloids, saponins and tannins are nitrogen- and glycoside-based secondary metabolites that provide diverse biological benefits. Although, present in lower concentrations, alkaloids contribute to the antimicrobial and anti-inflammatory properties of pulses. They act as defense molecules against pathogens and have been linked to immune-regulating activity in humans. Saponins, abundant in chickpeas and lentils, are amphiphilic glycosides known for their surface-active properties. Their molecular structure consists of a hydrophobic aglycone linked to one or more sugar chains. Nutritionally, saponins are recognized for their ability to bind cholesterol and bile acids in the intestine, leading to reduced cholesterol absorption and improved lipid metabolism. They also stimulate the immune system and exhibit anticarcinogenic activity through modulation of cell signaling pathways and apoptosis in malignant cells.Tannins, particularly condensed tannins or proanthocyanidins, contribute to both antinutritional and beneficial effects depending on their concentration. At high levels, tannins can form complexes with proteins and minerals, reducing digestibility; however, at moderate levels, they act as powerful antioxidants. These compounds stabilize cell membranes, inhibit lipid peroxidation and protect against oxidative damage. The balance between beneficial and inhibitory effects of tannins can be optimized through controlled processing, such as soaking, boiling and fermentation, which lower their concentration without diminishing antioxidant potential (Mekkaranikarthil Sudhakaran and Bukkan, 2021)

3.3 Isoflavones and other polyphenols

Isoflavones are a unique group of polyphenols with structural similarity to estrogens, enabling them to act as phytoestrogens in mammals. Common isoflavones such as daidzein, genistein and formononetin are found in varying levels in chickpeas, lentils and peas. These compounds interact with estrogen receptors, offering protective effects against hormone-dependent cancers, menopausal symptoms and osteoporosis. In addition to their estrogenic activity, isoflavones have been associated with modulation of lipid metabolism and glucose homeostasis. They reduce oxidative stress by enhancing endogenous antioxidant enzymes such as superoxide dismutase and glutathione peroxidase. Beyond isoflavones, pulses also contain lignans and stilbenes polyphenolic compounds that further strengthen their antioxidant and anti-inflammatory properties (Obadi *et al*., 2021). The bioavailability of these compounds is influenced by gut microbiota, which can biotransform them into more active metabolites such as equol. Thus, the health effects of polyphenols are not only determined by their concentration in pulses but also by individual metabolic responses and dietary patterns.

3.4 Carotenoids and tocopherols

Pulses contain several fat-soluble antioxidants that complement their phenolic profile. Carotenoids, including β-carotene, lutein and zeaxanthin, are abundant in colored pulses such as red lentils and black grams. These pigments play key roles in protecting cells from photo-oxidative damage by quenching singlet oxygen and free radicals. β-Carotene also serves as a provitamin A compound, contributing to vision and immune health.Tocopherols, the most biologically active forms of vitamin E, are integral components of the lipid fraction of pulses. α-Tocopherol and γ-tocopherol are the predominant isoforms, acting as lipid-phase antioxidants that prevent the propagation of free radical reactions in cell membranes. The combination of carotenoids and tocopherols enhances overall oxidative stability, ensuring both physiological benefits and improved shelf-life of pulse-based products (Maheshwari *et al*., 2022). These lipophilic antioxidants are relatively heat-stable and can withstand moderate processing conditions. However, prolonged exposure to high temperatures and oxygen can degrade their structure. Hence, optimizing storage and cooking conditions is essential to preserve these valuable micronutrients.

3.5 Phytosterols and other bioactive lipids

Phytosterols are plant-derived sterols structurally similar to cholesterol, contributing to the hypocholesterolaemia effects associated with pulse consumption. They competitively inhibit intestinal absorption of cholesterol, resulting in reduced plasma LDL cholesterol levels. Major phytosterols in pulses include β-sitosterol, campesterol and stigmasterol. Beyond sterols, pulses contain bioactive lipids such as phospholipids and glycolipids that play essential roles in maintaining cellular integrity and signal transduction. These compounds have been linked to improved cardiovascular and hepatic functions. The synergistic interaction between phytosterols, tocopherols and phenolic compounds enhance the overall antioxidant and anti-inflammatory potential of pulses, supporting their functional food value (Chandran *et al*., 2020).

3.6 Environmental and processing influences on phytochemicals

The accumulation and stability of phytochemicals in pulses are strongly influenced by agronomic and postharvest factors. Environmental variables such as light intensity, temperature, soil fertility and water availability significantly affect secondary metabolite synthesis. Drought and moderate stress conditions often enhance phenolic accumulation as part of the plant's defense mechanism. Processing methods can either degrade or enhance phytochemical levels depending on the technique. Traditional methods such as soaking and boiling may cause leaching of water-soluble compounds, whereas germination and fermentation increase total phenolic content by activating hydrolytic enzymes (Pathan and Siddiqui, 2022). Emerging processing technologies such as ultrasound-assisted, microwave-assisted and enzyme-aided treatments have shown promise in improving the extractability and antioxidant capacity of pulse phytochemicals while maintaining nutritional integrity. Storage conditions also play a role in phytochemical preservation. Controlled temperature and humidity help prevent oxidation and degradation of phenolics, flavonoids and carotenoids, thereby maintaining their functional quality throughout shelf life.

4. Antioxidant potential of pulses

Pulses are increasingly valued for their outstanding antioxidant potential, which plays a critical role in maintaining physiological health and preventing oxidative stress-related disorders. Their antioxidant activity is primarily attributed to a diverse range of bioactive compounds, including phenolic acids, flavonoids, tannins, saponins, carotenoids, tocopherols and phytosterols. These compounds act through multiple biochemical mechanisms, neutralizing reactive oxygen species (ROS), chelating metal ions, inhibiting lipid peroxidation and enhancing endogenous antioxidant defences.The antioxidant capacity of pulses has become a focal point in nutritional and phytomedicinal research, given its direct association with the prevention of chronic degenerative diseases such as diabetes, cardiovascular diseases and cancer. The following subsections elaborate on the underlying mechanisms, influencing factors and biological significance of pulse-derived antioxidants (Batiha *et al*., 2023).

4.1 Mechanisms of antioxidant action

Antioxidants in pulses act through a variety of complementary mechanisms, offering broad-spectrum protection against oxidative damage (Figure 2).

4.1.1 Free radical scavenging activity

Free radicals such as superoxide anion, hydroxyl radical and peroxyl radicals are by-products of cellular metabolism and environmental stress. If not neutralized, they initiate oxidative chain reactions that damage lipids, proteins and DNA. Phenolic compounds and flavonoids in pulses act as hydrogen or electron donors, neutralizing free radicals and terminating oxidative chain reactions (Jimenez-Lopez *et al*., 2020). The conjugated aromatic structures of these compounds stabilize the unpaired electron of radicals, preventing further oxidative reactions.

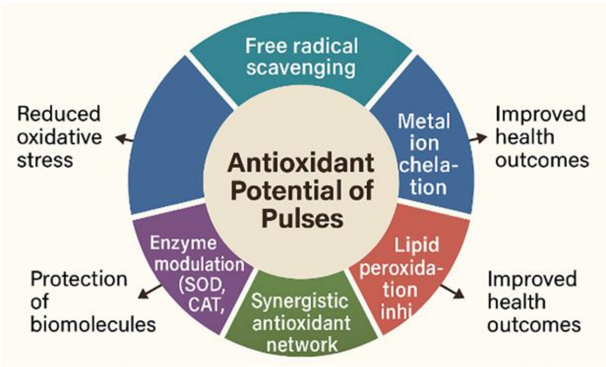

Figure 2: Mechanisms of antioxidant action of pulses.

4.1.2 Metal chelation

Transition metals, particularly iron and copper, catalyze the production of highly reactive hydroxyl radicals through Fenton and Haber-Weiss reactions. Chelation of these metals by polyphenolic compounds prevents them from participating in such redox reactions. The metal-binding ability of phenolics and tannins in pulses thereby limits pro-oxidant activity and protects cellular components from oxidative stress (Devkota *et al*., 2022).

4.1.3 Inhibition of lipid peroxidation

Pulses contain lipid-phase antioxidants such as carotenoids and tocopherols that play vital roles in preventing lipid peroxidation. These lipophilic compounds protect membrane lipids and plasma lipoproteins from oxidative degradation by intercepting lipid radicals and terminating peroxidation chain reactions (Ciudad-Mulero *et al*., 2020). The prevention of lipid peroxidation is particularly important for cardiovascular health, as it reduces the formation of oxidized low-density lipoproteins (ox-LDL), which are major contributors to atherosclerosis.

4.1.4 Enhancement of endogenous antioxidant enzymes

In addition to providing direct antioxidant activity, pulse bioactives upregulate the expression and activity of endogenous antioxidant enzymes such as superoxide dismutase (SOD), catalase (CAT) and glutathione peroxidase (GPx). Isoflavones and phenolics in pulses activate the nuclear factor erythroid 2-related factor 2 (Nrf2) signaling pathway, which regulates antioxidant gene expression. This adaptive mechanism strengthens the body's intrinsic antioxidant defense system, offering long-term protection against oxidative stress (Alam *et al*., 2022).

4.1.5 Synergistic and additive effects

The antioxidant efficacy of pulses results from the synergistic interaction of multiple compounds rather than the action of a single molecule. Hydrophilic antioxidants such as phenolics act in aqueous environments, while lipophilic compounds such as tocopherols and carotenoids operate within lipid membranes. This dual-phase antioxidant system ensures comprehensive protection across cellular compartments, illustrating the holistic nature of pulse antioxidants (Sinkovièet *al*., 2022).

4.2 Experimental assessment of antioxidant capacity

The antioxidant potential of pulses is widely studied through various *in vitro* analytical assays that quantify different modes of antioxidant action. The DPPH (2,2-diphenyl-1-picrylhydrazyl) assay measures the capacity of pulse extracts to neutralize free radicals by hydrogen atom donation, reflected by a decrease in absorbance. The ABTS (2,22 -azinobis (3-ethylbenzothiazoline-6-sulfonic acid)) assay evaluates the ability of antioxidants to quench radical cations, representing both hydrophilic and lipophilic activity. The ferric reducing antioxidant power (FRAP) assay assesses the reducing power of antioxidants by converting ferrous ions (Fe^{2}) to ferrous ions (Fe²z). Other assays such as the ORAC (Oxygen Radical Absorbance Capacity) method measure the inhibition of peroxyl radical-induced oxidation, reflecting the chain-breaking antioxidant capacity (Shahidi and Hossain, 2023). Additionally, metal-chelating and lipid peroxidation inhibition assays provide complementary evidence of the antioxidant efficacy of pulse extracts. Collectively, these analytical approaches confirm that pulses exhibit substantial antioxidant activity comparable to that of well-known functional foods such as berries and green tea.

4.3 Factors influencing antioxidant activity

The antioxidant potential of pulses is highly variable and influenced by genetic, environmental and technological factors.

4.3.1 Species and cultivar differences

Different pulse species and cultivars display distinct antioxidant capacities. Dark-colored pulses, such as black gram and red lentil, generally exhibit higher total phenolic and flavonoid contents than light-colored varieties. This variation is largely due to differences in seed coat pigmentation, phenolic biosynthesis pathways and genetic traits influencing secondary metabolite accumulation (Shevkani *et al*., 2022).

4.3.2 Environmental and agronomic conditions

Environmental factors such as soil fertility, temperature, sunlight exposure and water availability significantly influence the synthesis of antioxidant compounds. Moderate abiotic stresses, such as drought or nutrient limitation, stimulate the accumulation of phenolics and flavonoids as part of the plant's adaptive defense mechanism. Organic farming systems have also been shown to enhance the antioxidant content of pulses due to the activation of natural stress responses (Rajagukguk *et al*., 2022).

4.3.3 Processing and technological treatments

Processing methods have a profound effect on the antioxidant profile of pulses. Traditional methods such as soaking, boiling and roasting can cause some loss of heat-sensitive phenolics but also improve bioavailability by releasing bound phenolic acids from cell wall matrices. Germination and fermentation significantly increase total phenolic content and antioxidant activity by activating hydrolytic enzymes that break down complex polyphenols into more bioactive forms. Recent advancements in food processing technologies, such as microwave-assisted extraction, ultrasound-assisted treatment and enzymatic hydrolysis, have been successfully employed to enhance the recovery and retention of antioxidants from pulses (Mekky *et al*., 2020). These innovations ensure that processed pulse-based products retain their functional quality and health-promoting properties.

4.3.4 Storage stability

The antioxidant stability of pulses during storage is influenced by moisture, temperature and light exposure. Phenolic compounds are relatively stable under controlled conditions, while carotenoids and tocopherols are prone to degradation upon prolonged exposure to oxygen and heat. Proper storage under low humidity and cool temperatures preserves the antioxidant potential of pulses over extended periods.

4.4 Correlation between phytochemical composition and antioxidant activity

The antioxidant capacity of pulses is strongly correlated with their total phenolic content (TPC) and total flavonoid content (TFC). Pulses with higher phenolic concentrations typically demonstrate stronger radical-scavenging and metal-chelating abilities. The type and structure of phenolic compounds also influence antioxidant strength flavonols and catechins, for instance, exhibit higher reducing power due to the presence of multiple hydroxyl groups and conjugated bonds. Although, phenolic compounds contribute the most to antioxidant activity, other constituents such as carotenoids, tocopherols and saponins also enhance overall antioxidant performance through complementary mechanisms (Szczepañska *et al*., 2021). The combined antioxidant network in pulses provides both rapid and sustained defence against oxidative damage, reflecting their holistic nutraceutical value.

4.5 Physiological and therapeutic relevance of pulse antioxidants

The potent antioxidant properties of pulses translate into significant health benefits for humans. Regular consumption of pulses has been associated with improved oxidative balance, reduced lipid peroxidation and enhanced resistance to oxidative stress-related disorders. The antioxidant defence provided by pulse phytochemicals helps protect against the pathogenesis of cardiovascular diseases, diabetes and neurodegenerative conditions by preserving vascular and cellular integrity. Pulse antioxidants also play an important role in preventing DNA damage and mutagenesis, contributing to their anticancer potential. Furthermore, by reducing inflammatory oxidative mediators, they alleviate chronic inflammation and improve immune resilience. These multifaceted biological actions make pulses vital components of functional diets aimed at promoting long-term health and preventing lifestyle-related diseases (Alam *et al*., 2022).

5. Phytomedicinal properties and health benefits of pulses

Pulses are increasingly recognized not only as nutrient-dense foods but also as functional ingredients with broad therapeutic and preventive health benefits. Their phytochemical constituents phenolics, flavonoids, saponins, phytosterols, isoflavones and carotenoids contribute to their pharmacological properties through antioxidant, anti-inflammatory, antidiabetic, cardioprotective, anticancer and antimicrobial mechanisms. These health-promoting effects arise from their ability to regulate key metabolic pathways, modulate gut microbiota and maintain physiological homeostasis.The following subsections highlight the major phytomedicinal attributes of pulses and their relevance in modern nutrition and preventive medicine.

5.1 Antidiabetic and hypoglycemic effects

Pulses exert strong antidiabetic potential due to their low glycemic index, high fiber content and abundance of polyphenols that influence glucose metabolism. The slow-digesting starch and resistant starch fractions delay glucose absorption, preventing rapid spikes in blood sugar after meals. Dietary fiber further contributes by increasing satiety and enhancing insulin sensitivity. Bioactive compounds such as phenolic acids, flavonoids and saponins play a crucial role in improving glucose homeostasis. These compounds inhibit carbohydrate-hydrolyzing enzymes such as α-amylase and α-glucosidase in the intestinal lumen, thereby reducing the rate of starch breakdown and glucose release. In addition, certain flavonoids activate AMP-activated protein kinase (AMPK), a key enzyme in cellular energy regulation, promoting glucose uptake in muscle and liver cells. Pulses such as lentils, chickpeas and black grams have demonstrated the ability to lower fasting blood glucose and glycated hemoglobin (HbA1c) levels when consumed regularly (Abarajitha *et al*., 2025). Germination and fermentation further enhance their hypoglycemic potential by increasing the bioavailability of phenolic compounds and short-chain peptides. Thus, pulses can be considered natural antidiabetic agents that provide both nutritional and therapeutic benefits.

5.2 Antihyperlipidemic and cardioprotective roles

Cardiovascular protection is one of the most significant health benefits associated with pulse consumption. The low-fat, high-fiber and high-protein profile of pulses, combined with the presence of phytosterols and saponins, makes them highly effective in lowering cholesterol and improving lipid metabolism. Saponins reduce intestinal absorption of dietary cholesterol by forming insoluble complexes with bile acids, thereby promoting their excretion. Phytosterols compete with cholesterol for absorption sites in the intestinal mucosa, effectively lowering total and low-density lipoprotein (LDL) cholesterol concentrations. In addition, the high potassium and magnesium content of pulses helps regulate blood pressure and maintain electrolyte balance. Regular intake of pulses is linked with improved endothelial function and reduced risk of atherosclerosis. The antioxidant properties of flavonoids and tocopherols protect low-density lipoproteins from oxidative modification - a critical step in plaque formation. Furthermore, pulse-derived peptides have been shown to inhibit angiotensin-converting enzyme (ACE), contributing to vasodilation and blood pressure regulation. Together, these mechanisms underscore the cardioprotective potential of pulses as natural agents for cardiovascular health management.

5.3 Anticancer activity

Pulses possess strong anticancer potential attributed to the synergistic effects of their polyphenols, isoflavones and saponins. These compounds influence cancer cell proliferation, apoptosis and cell cycle progression through multiple molecular pathways. Phenolic acids such as ferulic and caffeic acids act as free radical scavengers, protecting DNA from oxidative damage that can initiate tumor formation. Isoflavones, particularly genistein and daidzein, exhibit estrogen-modulating activity and inhibit the growth of hormone-dependent cancers such as breast and prostate cancer. They bind to estrogen receptors, reducing the activity of endogenous estrogens and suppressing tumor-promoting gene expression. Saponins induce apoptosis in cancer cells by activating caspase-dependent pathways and disrupting tumor cell membranes (Awoke *et al*., 2025). In addition to direct anticancer effects, pulses contribute to cancer prevention by promoting detoxification enzymes such as glutathione-S-transferase and enhancing the elimination of carcinogens. The presence of resistant starch and dietary fiber further aids in colon cancer prevention by increasing fecal bulk, diluting carcinogenic compounds and promoting the production of protective short-chain fatty acids in the colon. Thus, regular consumption of pulses serves as an effective dietary strategy for cancer prevention and management.

5.4 Anti-inflammatory and immunomodulatory effects

Chronic inflammation is a key contributor to various metabolic and degenerative diseases. Pulses contain several anti-inflammatory phytochemicals that suppress inflammatory pathways and cytokine production. Flavonoids and phenolic acids inhibit pro-inflammatory mediators such as nitric oxide, prostaglandins and tumor necrosis factor-alpha (TNF-α) by modulating transcription factors like nuclear factor kappa B (NF-κB). Saponins and phytosterols exhibit immunomodulatory properties by enhancing the activity of natural killer cells and macrophages, which are vital for immune defense. Polyphenols help balance pro- and anti-inflammatory cytokines, maintaining immune homeostasis. Additionally, pulse proteins and peptides possess antioxidant and anti-inflammatory bioactivity, further supporting tissue protection against oxidative and inflammatory stress.The regular inclusion of pulses in the diet has been linked to reduced markers of systemic inflammation such as C-reactive protein (CRP). This anti-inflammatory capacity supports the role of pulses as functional foods for managing metabolic disorders, autoimmune conditions and age-related degenerative diseases (Gangadharan *et al*., 2025).

5.5 Antimicrobial and gut health benefits

Pulses contribute significantly to gut health through their dietary fiber, resistant starch and polyphenolic content. These components act as prebiotics, selectively stimulating the growth of beneficial gut bacteria such as *Bifidobacterium* and *Lactobacillus*. The fermentation of resistant starch and fiber by gut microbes results in the production of short-chain fatty acids like acetate, propionate and butyrate, which improve intestinal barrier function, modulate immune responses and inhibit pathogen growth. Polyphenols and saponins in pulses also exhibit antimicrobial activity against pathogenic bacteria and fungi. They disrupt microbial membranes, inhibit enzyme activity and prevent biofilm formation. These actions contribute to maintaining a healthy gut microbiota composition, reducing gastrointestinal infections and promoting digestive wellness. Furthermore, the interaction between pulse bioactives and gut microbiota produces bioactive metabolites that enhance systemic antioxidant and anti-inflammatory effects. This gut-mediated mechanism underscores the significance of pulses in promoting holistic gastrointestinal and metabolic health.

5.6 Neuroprotective and cognitive health effects

Emerging evidence suggests that pulses may play a role in protecting brain health and mitigating neurodegenerative conditions. Their polyphenols and isoflavones possess neuroprotective properties, reducing oxidative stress in neuronal tissues and preventing neuroinflammation. Phenolics enhance neuronal antioxidant defenses and modulate signaling pathways associated with synaptic plasticity and memory retention. The low glycemic index of pulses contributes to stable glucose supply to the brain, which is crucial for cognitive performance (Abarajitha *et al*., 2025). In addition, the folate and magnesium content in pulses supports neurotransmitter synthesis and nerve conduction. Regular consumption of pulses has been associated with reduced risk of cognitive decline, Alzheimer's disease and other age-related neurological disorders.

5.7 Hepatoprotective and detoxifying effects

Pulses also exhibit hepatoprotective effects through their antioxidant, anti-inflammatory and detoxifying activities. Phenolics and flavonoids neutralize free radicals generated during hepatic metabolism, protecting liver cells from oxidative injury. Saponins and isoflavones promote lipid metabolism and prevent hepatic fat accumulation, thereby reducing the risk of non-alcoholic fatty liver disease. Additionally, pulses enhance the activity of detoxifying enzymes such as catalase, superoxide dismutase and glutathione peroxidase, facilitating the elimination of xenobiotics and heavy metals (Awoke *et al*., 2025). Their high fiber content also aids in bile acid excretion, supporting liver detoxification and cholesterol regulation. Consequently, the regular intake of pulses can play a key role in maintaining liver function and metabolic balance.

6. Pulses as functional foods and nutraceutical ingredients

The growing global interest in functional foods and nutraceuticals has placed pulses at the forefront of health-oriented dietary research and innovation. Beyond their traditional role as staple foods, pulses are now being valorized as rich sources of bioactive compounds that provide targeted physiological benefits beyond basic nutrition. Their unique combination of high-quality proteins, complex carbohydrates, dietary fiber, vitamins, minerals and phytochemicals make them ideal candidates for functional food formulations and nutraceutical product development.The functional attributes of pulses arise from their ability to modulate metabolic processes, improve gut health, regulate lipid and glucose metabolism and strengthen antioxidant defense systems. This multifunctional nature has spurred the development of various pulse-based ingredients and products designed to meet modern nutritional, therapeutic and environmental needs.

6.1 Concept of pulses as functional foods

Functional foods are defined as foods that, in addition to providing essential nutrients, exert beneficial effects on one or more target functions in the body, thereby improving health and reducing disease risk. Pulses exemplify this concept through their rich nutrient density and abundance of health-promoting phytochemicals.They are naturally gluten-free, low in fat and rich in dietary fiber, making them suitable for individuals with celiac disease, diabetes and cardiovascular disorders. The presence of resistant starch, oligosaccharides and phenolic antioxidants in pulses provides physiological benefits such as improved digestion, blood sugar regulation and cholesterol reduction. Moreover, their low glycemic index ensures slow glucose release, promoting sustained energy levels and preventing postprandial hyperglycaemia.Incorporating pulses into regular diets enhances the nutritional quality of meals and contributes to disease prevention. As consumers increasingly seek plant-based, sustainable and health-promoting foods, pulses represent a cornerstone in functional food innovation (Cuevas-Rodríguez *et al*., 2025).

6.2 Pulses in nutraceutical development

Nutraceuticals are bioactive compounds derived from foods that provide medical or health benefits, including the prevention and treatment of disease. Pulses serve as rich sources of such compounds, including phenolics, flavonoids, saponins, phytosterols and bioactive peptides. Pulse protein isolates and hydrolysates are used in nutraceutical formulations for their antioxidant, antihypertensive and cholesterol-lowering properties. These proteins, when enzymatically hydrolyzed, yield bioactive peptides that modulate physiological functions such as enzyme inhibition, hormone regulation and immune modulation. For instance, pulse-derived peptides have demonstrated angiotensin-converting enzyme (ACE) inhibitory activity, which helps regulate blood pressure and cardiovascular health. Polyphenol-rich extracts from pulses are incorporated into nutraceutical supplements aimed at improving metabolic balance, reducing oxidative stress and supporting cognitive and hepatic functions. Additionally, saponins and phytosterols are increasingly being used as natural cholesterol-lowering agents in nutraceutical formulations (Escobedo and Mojica, 2021). The natural, non-toxic and cost-effective profile of pulse bioactives provides a sustainable alternative to synthetic supplements.

6.3 Applications in functional food products

Pulses have found wide-ranging applications in developing functional food products catering to specific health needs. In the bakery sector, pulse flour is used in bread, biscuits and pasta to increase protein, fiber and mineral content while improving satiety. Fermented pulse-based foods, such as tempeh and dhokla, provide enhanced bioavailability of vitamins and minerals, along with probiotic benefits.In beverages, pulse protein isolates are used to produce dairy alternatives such as protein-enriched shakes, smoothies and yogurts. Snack industries have introduced roasted, puffed and extruded pulse-based snacks as healthier options with high protein and low oil content. Moreover, pulse-based infant formulas, meal replacements and gluten-free products are gaining popularity due to their balanced nutrient profiles and hypoallergenic properties. Emerging innovations include the incorporation of pulse bioactives into energy bars, nutraceutical capsules and encapsulated antioxidant powders (Palomares-Navarro *et al*., 2023). These products not only extend shelf life but also deliver targeted health benefits, making pulses indispensable to the growing global functional food market.

6.4 Nutraceutical mechanisms and physiological benefits

The physiological effects of pulse-based nutraceuticals are attributed to their complex composition of bioactive acting through multiple biochemical pathways. Polyphenols, carotenoids and tocopherols scavenge free radicals and reduce oxidative stress, thereby protecting cellular structures from damage. Saponins and phytosterols regulate lipid metabolism by reducing cholesterol absorption and promoting bile acid excretion. Protein-derived peptides influence blood pressure regulation through ACE inhibition, while resistant starch and dietary fiber improve glucose metabolism and gut health. The synergistic action of these compounds enhances metabolic efficiency, reduces inflammatory responses and strengthens immune function (Palomares-Navarro*et al*., 2023). Continuous consumption of pulse-based nutraceuticals contributes to overall health maintenance and prevention of chronic diseases such as diabetes, obesity, cardiovascular disorders and certain cancers.

6.5 Industrial trends and market potential

The global demand for pulse-based functional foods and nutraceuticals is rapidly growing due to shifting consumer preferences toward plant-based and sustainable diets. Pulses are recognized as environmentally friendly crops with low carbon footprints, minimal water requirements and high protein productivity. These characteristics align well with the global movement toward climate-resilient and sustainable food systems. Food industries are increasingly investing in developing innovative pulse-based formulations that meet clean-label, allergen-free and non-GMO standards. The market for pulse ingredients - especially protein isolates and floursis expanding across North America, Europe and Asia-Pacific. The growing vegan and vegetarian population further accelerates the demand for pulses as natural alternatives to animal-based proteins. Governments and health organizations worldwide promote the inclusion of pulses in daily diets as part of sustainable nutrition initiatives. The recognition of pulses by the United Nations during the International Year of Pulses has reinforced their importance as both nutritional and economic assets in achieving global food security (Escobedo and Mojica, 2021).

7. Challenges and future prospects

Despite their proven nutritional superiority and health-promoting attributes, pulses remain underutilized in both human diets and industrial applications compared to cereals and oilseeds. Although, the scientific evidence supporting their functional and nutraceutical potential continues to expand, several challenges limit their wide spread integration into modern food systems. These challenges span multiple domains, including processing limitations, bioavailability of phytochemicals, sensory acceptability, production constraints and consumer awareness.To harness the full potential of pulses as functional foods and nutraceuticals, a multi-dimensional approach involving technological innovation, scientific research, sustainable production and policy support is required. This section explores the current limitations and outlines future strategies for expanding the role of pulses in global health and nutrition.The future of pulses as functional foods and nutraceutical ingredients is exceptionally promising. Advances in food processing technologies, molecular biology and functional genomics offer vast opportunities to enhance both the nutritional quality and therapeutic efficacy of pulses. The integration of green processing methods, precision nutrition and personalized dietary approaches will redefine their role in human health management. Promoting public awareness about the nutritional and environmental advantages of pulses can drive consumer demand and encourage dietary diversification. Policymakers should prioritize pulses within food security and health promotion frameworks, ensuring research funding, infrastructure development and farmer incentives. Ultimately, a collaborative approach involving agricultural scientists, food technologists, nutritionists and policymakers is essential to fully realize the potential of pulses in addressing global challenges of malnutrition, chronic disease and environmental sustainability.

8. Conclusion

Pulses occupy a unique and indispensable position in the global food and nutrition landscape, bridging the gap between agricultural sustainability and human health. As nutrient-dense crops rich in high-quality proteins, complex carbohydrates, dietary fiber, vitamins, minerals and diverse phytochemicals, they represent an exceptional natural resource for combating malnutrition, metabolic disorders and degenerative diseases. Beyond their nutritional contributions, the wide spectrum of bioactive compounds as phenolics, flavonoids, saponins, phytosterols, isoflavones, carotenoids and tocopherols-endows pulses with remarkable antioxidant and phytomedicinal properties that confer protection against oxidative stress, inflammation and chronic diseases. The growing body of scientific evidence substantiates the classification of pulses as functional foods and nutraceutical ingredients. Their ability to modulate blood glucose, lipid profiles, immune responses and gut microbiota underscores their role in disease prevention and overall wellness. Moreover, their low environmental footprint, nitrogen-fixing capacity and adaptability to diverse agro-ecological zones make them integral to sustainable food systems and climate-resilient agriculture. However, despite their tremendous potential, the full utilization of pulses in food and health industries remains constrained by several technological, nutritional and socio-economic challenges.

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Conflict of interest

The authors declare no conflicts of interest relevant to this article.

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