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A Comprehensive Review on Key Chemical Constituents of Indian Pulses and Their Multifaceted Health Benefits in a Global Context

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ABSTRACT

Pulses are edible seeds of legume plants, but they are distinct from legumes because they are dried seeds before consumption. Because of their economic value and high nutritional content, pulses are integral to diets worldwide. Various pulses such as *Macrotyloma uniflorum* (horse gram), *Glycine max* (soybeans), *Pisum sativum* (field peas), *Lens esculenta* (lentils), *Vigna mungo* (black gram), *Vigna unguiculata* (cowpeas), *Vigna angularis* (adzuki beans), *Vigna radiata* (green gram), *Vicia faba* (broad beans), *Phaseolus* sp. (common beans), *Cajanus cajan L.* (pigeon peas), and *Lathyrus sativus* (Lathyrus) are grown extensively worldwide. Pulses also contain various bioactive compounds such as polyphenols and phytosterols, which possess various pharmacological properties. These pharmacologically active chemical constituents have attained remarkable attention in the prevention and management of chronic diseases like diabetes, cardiovascular diseases, cancer, and obesity. These compounds also have prebiotic, anti-inflammatory, and antioxidant properties. The present study focuses on current information on pharmacologically active chemical constituents such as polyphenols, phytosterols, resistant starch, and oligosaccharides obtained from pulses. This article also focuses on the multifaceted biological roles and health implications of Indian pulses and their industrial usage. The pulses are a source of natural antioxidant, anti-inflammatory, anticancer, antidiabetic, and antimicrobial constituents. The biochemical potential of these pulses, along with future perspectives, is discussed in greater detail in this review.

1 | Introduction

Pulses play a crucial role in ensuring nutritional and environmentally friendly farming, but their popularity has fallen as crops like cereals have gained popularity. They are not only good for health, but they also help to improve the soil and maintain consistent agricultural yields (Agarwal and Devra 2024). Around the world, pulse farming areas have expanded marginally, whereas the production ratio has declined. The trade in pulses has expanded dramatically over the years (Ahmad et al. 2018). All around the world, billions of people consume pulses as a nutritional supplement (P. Singh et al. 2017). At present, more than 173 countries grow and trade pulses, with India, Canada, China, Myanmar, and Nigeria among the leading producers. Canada is especially known for its export capacity, as over 80% of its pulse harvest is

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transported abroad (Silva et al. 2020). Further, the analysis of arable land utilised for pulse production worldwide has shown that the highest percentage is covered in Southeast Asian countries (Myanmar, i.e., 36%); other countries involved are Niger (30.6%), Kenya (27%), Mozambique (22%), and Burkina Faso (20%), whereas countries like India, Pakistan, Mexico, Nigeria, Uganda, Tanzania, and Ethiopia have 10%–18% of their land involved in the production of pulses. The above data show the importance of pulses in the cropping system of low-income countries, where most production comes from small farms (Joshi and Rao 2017; Nigam et al. 2021). Pulses are cultivated in many parts of the world, but Asia, particularly India, produces nearly half of the total global supply (Didinger and Thompson 2021).

India is the world's foremost producer, user, and importer of pulses, sometimes known as the "poor man's meat" because of its high protein content and limited intake of dairy and animal products among populations with limited access to animal-based foods (Varma and Vishwanath 2023). They are extremely nutritious foods, supplying high amounts of plant protein, energy, minerals, vitamins, fiber, and other bioactive compounds (Biscarrat et al. 2024). When compared to cereals, pulses contain significantly higher amounts of iron (1.67 times), protein (2.47 times), vitamin A (3.54 times), and folate (5.31 times), making them a crucial component of a balanced diet according to NAAS 2022 (Biscarrat et al. 2024). Additionally, pulses complement cereals in vegetarian diets by balancing amino acid profiles, thereby improving overall protein quality. In India, cereals are the primary source of protein; however, they are poor in lysine and difficult to digest (Minocha et al. 2019). Research shows that the risk of inadequate quality protein intake ranges from 4% to 26% across age groups and 19% to 49% across states. Pulses, being an affordable non–animal protein option, are an important part of the Indian diet (Minocha et al. 2017). However, despite rising demand, inconsistent manufacturing and fluctuating costs have often caused shortages (Abraham and Pingali 2021).

Nutrition plays a vital role in health and well-being across all life stages (Jumrani and Rai 2020). In India, pulses contribute significantly to the national food basket, producing 25.75 million tonnes, accounting for about 9% of total food grain output in 2021–2022. The majority of production comes from chickpea, pigeon pea, black gram, mung bean, and lentil, which together account for nearly 90% of total pulse production. The primary pulse-producing states are Madhya Pradesh, Rajasthan, Maharashtra, Uttar Pradesh, Karnataka, Gujarat, and Andhra Pradesh, contributing 84% of the nation's pulse output during this period (Murugananthi et al. 2024). Between 2009–2010 and 2020–2021, India's pulse production grew from 18.17 to 27.93 million tonnes, recording an annual growth rate of about 3.73%, although unforeseen levels of agricultural output, global hunger, and malnutrition remain. The Food and Agriculture Organization (FAO) 2024 report shows that in 2023, approximately 713–757 million people, around 9.1% of the world's population, were undernourished ("Our office|FAO in India|Food and Agriculture Organization of the United Nations. www.fao.org. https://www.fao.org/india/fao-in-india").

The FAO Country Programming Framework (CPF) 2023–2027, developed with India under NITI Aayog, aligns with the United Nations Sustainable Development Cooperation Framework (UNSDCF) goals. It focuses on transforming agrifood systems, doubling farmers' income, ensuring sustainability, and eliminating malnutrition in line with FAO's global strategies ("Programmes and projects|FAO in India|Food and Agriculture Organization of the United Nations. www.fao.org. https://www.fao.org/india/programmes-and-projects/en/"). India produces almost one-fourth of all the pulses in the world. Because the population is growing, we will require 38 million tons of pulses by 2030. In order to fulfill this demand, pulse production needs to increase by 2.2% every year (Murugananthi et al. 2024). Pulse-growing locations and production vary greatly across the country (S. Kumar and Bourai 2012).

Nutritionally, pulses are rich sources of plant-based protein, energy, dietary fiber, essential minerals, and various beneficial plant compounds. Because of their ability to improve diet quality and address nutrient deficiencies, pulses have been recognised as valuable in the global fight against malnutrition. This importance was acknowledged by the United Nations when it declared 2016 the "International Year of Pulses." Pulses are a major source of food and nutrition for people across the globe. Although all pulses come under the category of legumes, not every legume is classified as a pulse. Pulses, defined as the dry edible seeds of leguminous plants from the Fabaceae family, exclude crops consumed fresh (such as green peas and green beans) and those cultivated primarily for oil extraction (such as soybean and groundnut) (Sadohara et al. 2025). The term "legumes" covers the entire plant, whereas "pulses" specifically refers to these dried seeds. Commonly grown varieties include *Phaseolus vulgaris* (common beans), *Cicer arietinum* (chickpeas), *Lens culinaris* (lentils), *Vigna unguiculata* (cowpeas), *Pisum sativum* (dry peas), *Vigna radiata* (mung beans), *Cajanus cajan* (pigeon pea), *Phaseolus lunatus* (lima beans), *Vicia faba* (faba bean), *Vigna aconitifolia* (moth beans), *Vigna subterranea* (Bambara nuts), and *Lupinus angustifolius* (lupins). These crops are extensively consumed across the world and are integral to both human and livestock diets (Perera et al. 2020; Siddiq et al. 2022). From an agricultural perspective, pulses offer substantial ecological benefits. Through symbiotic associations with nitrogen-fixing bacteria such as *Rhizobium*, they enrich soil fertility, reduce the need for synthetic fertilizers, and improve the sustainability of cropping systems. They also thrive in low-input and marginal lands, often grown as intercrops with cereals and oilseeds to enhance farm productivity (Crews and Peoples 2004).

Despite their nutritional and environmental value, pulse production faces challenges such as yield instability, susceptibility to pests and diseases, and price fluctuations. Moreover, antinutritional factors like lectins, phytates, tannins, and enzyme inhibitors—naturally present in pulses—can limit nutrient bioavailability (B. Singh, Singh, Shevkani, et al. 2017). These compounds, however, can be reduced through processing methods such as soaking, germination, fermentation, and cooking. Advances in breeding and postharvest technology are being explored to enhance pulse quality, reduce antinutritional content, and improve consumer acceptance. The processing considerations to remove such antinutritional factors include dehulling, which can separate seed coats from cotyledons. Seed coats can have specific phytochemicals, whereas the cotyledons (seed leaves) can be used as a source of protein

in vegetables. However, these compounds are primarily found in plant portions and sap, which may help prevent various diseases (J. Singh and Basu 2012). Given their multifaceted role in human nutrition, environmental sustainability, and agricultural profitability, pulses remain a critical focus for policymakers, researchers, and farmers. Strengthening production systems, improving value chains, and increasing awareness of their health benefits are essential to meet growing global demand while ensuring long-term food and nutritional security. Indian pulses, especially those from the Himalayas, are remarkable because they grow in very diverse climates, soils, and altitudes. Traditional small-scale farming and crop diversity in the hills provide these pulses with richer nutrition and special bioactive compounds compared to pulses from other countries. This makes them not only important for local diets but also valuable for health and food security (Meena 2017; Partap 1999). In India, the significant contribution to pulse production comes from the Himalayan belt. Figure 1B shows that pulses are excessively beneficial and a significant source of the human diet.

Beyond their agronomic and economic importance, pulses also have therapeutic importance, making them indispensable for both nutrition and health research. The nonnutritive bioactive compounds include enzyme inhibitors, lectins, saponins, phytates, phenolics, oligosaccharides, phytosterols, resistant starch, and polyphenols. These constituents are associated with a range of health-promoting effects, such as antioxidant, anti-inflammatory, antidiabetic, cardioprotective, anticancer, and prebiotic activities. Studies on pulses from the Indian Himalayan region (e.g., horse gram, kidney bean, soybean, and rice bean) have shown improvements in lipid metabolism, blood pressure regulation, glycemic control, and inflammatory responses, with processing methods reducing their antinutritional effects (Ahirwar and Khan 2023). Another Indian study reported that chickpea, green gram, and horse gram are particularly rich in antioxidant phenolics and flavonoids (such as gallic acid, ferulic acid, quercetin, and rutin), which contribute to their strong free radical scavenging capacity (B. Kumar et al. 2021). Table 1 presents different types of pulses along with their leading production countries and the major bioactive compounds reported in them.

2 | Chemical Constituents of Indian Pulses and Their Properties

Pulses contain diverse biomolecules, including proteins, complex carbohydrates (oligosaccharides and resistant starch), lipids, vitamins, minerals, and secondary metabolites. It includes phenolic acids, flavonoids, tannins, isoflavones, saponins, lectins, protease inhibitors, phytates, phytosterols, and certain plant-derived vitamins. Although present in small quantities, these extranutritional constituents act as bioactive compounds with antioxidant, anti-inflammatory, gut-modulatory, lipid-regulating, and enzyme-modulating effects. Their distribution varies within the seed. Compounds like phenolic acids, flavonoids, tannins, anthocyanins, and isoflavones are concentrated in the seed coat, particularly in darker varieties such as red kidney beans and black gram; dietary fiber and prebiotics are abundant in the whole seed; and omega-3 fatty acids occur in trace amounts as plant-based precursors (Langyan et al. 2022; Olas 2025). The various types of bioactive components are discussed in the section below.

2.1 | Polyphenols

Polyphenols are natural compounds that have one or more hydroxyl groups attached to an aromatic ring. They are mainly produced through the shikimic acid pathway and are considered secondary metabolites in higher plants. Polyphenols are classified into four main groups: phenolic acids, flavonoids, stilbenes, and lignans. These compounds are well known for their strong antioxidant properties and potential therapeutic benefits, including anti-inflammatory and anticancer effects. In pulses, important types of polyphenols include flavonols, phenolic acids, flavan-3-ols, and anthocyanins, which also help reduce tannin levels (B. Singh, Singh, Shevkani, et al. 2017).

Different pulses contain a variety of beneficial polyphenols. Chickpeas, garbanzo beans, and Bengal gram are rich in flavonoids like kaempferol and quercetin, as well as phenolic acids such as caffeic acid and ferulic acid, which are valued for their anti-inflammatory, anticancer, and skin-protective properties.

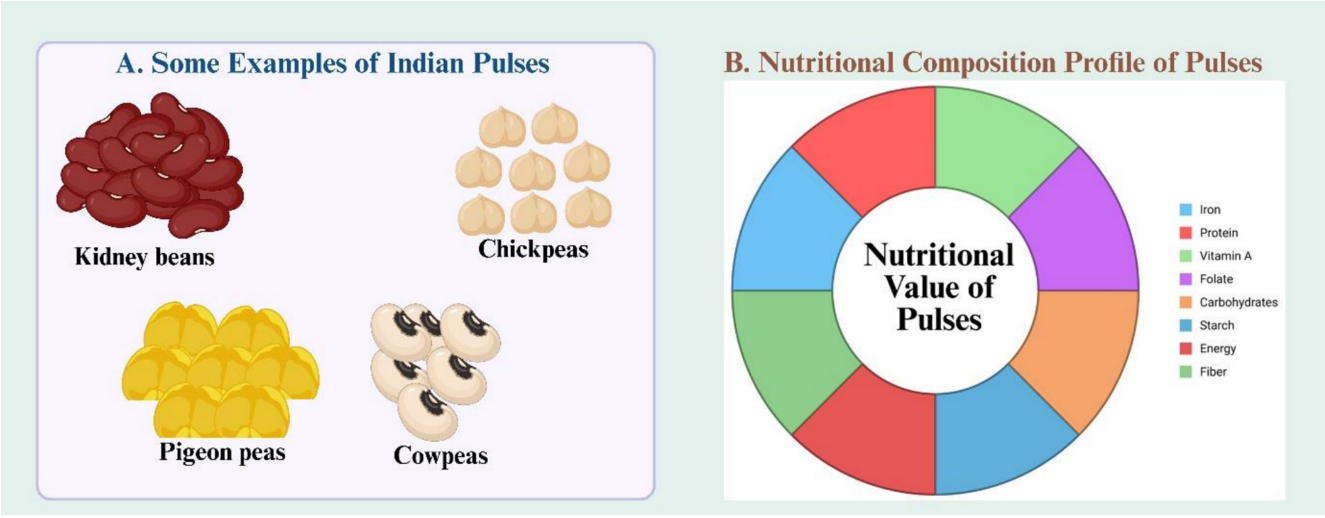


FIGURE 1 | (A) Examples of standard Indian pulses. (B) Nutritional composition profile of pulses: protein, fiber, fats, carbs, starch, and energy.

TABLE 1 | Significant types of pulses, their leading production countries, and associated bioactive components.

Sr. No.	Common name	Scientific name	Leading production countries	Key bioactive compounds/phytochemicals	Data on Indian-grown pulses
1	Kidney bean	*Phaseolus vulgaris*	India is included among the major producers globally	High dietary fiber, resistant starch, protein; notable phenolics (0.25- to 3.79-mg GAE/g), flavonoids (0.19- to 7.05-mg RE/g), and γ-tocopherol (L. Kan et al. 2017)	Data not available specifically for Indian-grown
2	Pigeon pea	*Cajanus cajan*	India, significant in Africa	Rich in phenolics, flavonoids, terpenoids, essential oils; antiviral, antioxidant, anti-inflammatory, hypoglycemic, and hypocholesterolemic effects (Bressani et al. 1986)	Data not available specifically for Indian-grown
3	Horse gram	*Macrotyloma uniflorum*	India (native and underutilized)	High in phenolic acids (ferulic, vanillic, and *p*-hydroxybenzoic), flavonoids (quercetin 129.5 mg, kaempferol 117.2 mg, and myricetin 35.5 mg per 100 g), saponins, tannins, phytic acid, oligosaccharides, and protease inhibitors; strong antioxidant, antidiabetic, and antiurolithiatic activities (Oli et al. 2024; Sah et al. 2023; Vashishth et al. 2022)	Indian horse gram is extensively studied and shows potent bioactive profiles.
4	Soybean	*Glycine max*	Brazil, the United States, and India notable	High in isoflavones (genistein and daidzein), saponins, protease inhibitors, phytoestrogens, lignan precursors (secoisolariciresinol), lunasin peptide with anticancer, anti-inflammatory, and cardioprotective benefits (Baweja et al. 2022)	Indian cultivars show comparable isoflavone levels to global varieties (558–1048 μg/g), similar antioxidant potential.
5	Green/Black Gram	*Vigna radiata*/*Vigna mungo*	India (major producer)	Rich in flavonoids (flavones and isoflavones), phenolic acids (gallic, vanillic, caffeic, and *p*-hydroxybenzoic), vitexin, isovitexin particularly abundant in mung bean; black gram has folate, enzyme inhibitors, lectins, phytosterols, phenolic compounds, saponins, and antioxidants (B. Kumar et al. 2021; Vashishth et al. 2022)	Indian varieties are well known for these phytochemicals, although comparative studies are lacking.
6	Lentil	*Lens culinaris*	India, Canada, and Australia	Diverse phenolics (phenolic acids, flavan-3-ols, proanthocyanidins, anthocyanidins, flavonols, flavones, and flavanones), and high in seed coats; plus saponins, carotenoids, tocopherols, and phytosterols	Data not available specifically for Indian-grown
7	Rice Bean	*Vigna umbellata*	South/Southeast Asia regions	Contains catechin-7-O-glucoside with antioxidant, cytoprotective activity (Lalramhlimi et al. 2018)	Data not available specifically for Indian-grown

(Continues)

TABLE 1 | (Continued)

Sr. No.	Common name	Scientific name	Leading production countries	Key bioactive compounds/phytochemicals	Data on Indian-grown pulses
8	Cowpea	*Vigna unguiculata*	Nigeria, Niger, and Brazil	Rich in unsaturated fatty acids, phospholipids (lecithin), tocols, carotenoids (lutein and β-carotene), and phytosterols; high phenolic content (e.g., 63- to 692-mg GAE/100 g), flavonoids (quercetin and kaempferol), anthocyanins (Sardar et al. 2024; Shevkani et al. 2025)	Data not available specifically for Indian-grown
9	Faba & Adzuki Beans	*Vicia faba/Vigna angularis*	China and Japan (adzuki); Europe and China (faba)	General pulses profile: phenolics, saponins, and lectins; specific comprehensive data unavailable (Lalramhlimi et al. 2018)	Data not available specifically for Indian-grown

Chickpeas also contain isoflavones like biochanin A and formononetin, which are used in hormone replacement therapies. Desi and Kabuli chickpeas are notable for flavonoids like apigenin and luteolin, which can suppress tumor growth and protect against oxidative stress.

Other pulses, such as kidney beans and common beans, are rich in catechin, epicatechin, gallic acid, and chlorogenic acid. They also contain colorful anthocyanins like cyanidin and delphinidin, especially in red and purple bean varieties. Peas have flavonoids such as rutin and quercetin, along with stilbenes like resveratrol. Lentils offer flavonoids like myricetin and isoquercetin, along with condensed tannins. Faba beans contain vitexin and isovitexin, whereas soybeans are known for isoflavones like genistein and daidzein. Pulses like horse gram, arhar, and pigeon pea also carry a variety of flavonoids, phenolic acids, and stilbenes, contributing to their nutritional and medicinal value (Durazzo et al. 2019).

2.1.1 | Flavonoids

Another class of polyphenolic compounds, which are characterized by a C6–C3–C6 skeleton and widely distributed across the plant kingdom, appear in fruits, vegetables, grains, bark, roots, stems, flowers, tea, and wine. It can be classified into seven major groups: flavones, flavonols, isoflavones, flavanones, flavanols, chalcones, and anthocyanins. Each class is distinguished by specific oxidation states and substitution patterns on the core skeleton. Pulses such as lentils, chickpeas, cowpeas, and mung beans are significant dietary sources of these compounds, particularly flavonols (e.g., quercetin and kaempferol) and flavones (e.g., luteolin and apigenin) (Parikh and Patel 2018). Their bioactivities include antioxidative, anti-inflammatory, antimutagenic, and anticarcinogenic effects, and they can modulate key cellular enzymes such as xanthine oxidase, cyclooxygenase, lipoxygenase, and phosphoinositide 3-kinase, although the detailed molecular mechanisms remain under investigation. In a survey of 27 Indian pulse varieties, total flavonoid content ranged from 18.3- to 344.7-mg rutin equivalents per 100 g, whereas total phenolics ranged from 38.6- to 542.7-mg gallic acid equivalents per 100 g, underscoring pulses as rich reservoirs of health-promoting phytochemicals (Baweja et al. 2022; Olas 2025).

2.2 | Phytosterols

Phytosterols, also known as plant sterols, are naturally found in pulses such as beans, chickpeas, peas, and lupins, mainly in their seeds (Wadhawan et al. 2021). These compounds are structurally similar to cholesterol and are known to reduce blood cholesterol levels by interfering with their absorption in the body (Berger et al. 2004). Pulses generally contain between 124 and 135 mg of phytosterols per 100 g of dry weight (DW). Kidney beans have about 127–134 mg, chickpeas range from 35 to 205 mg, peas have around 242 mg, and lentils contain about 158 mg per 100 g DW (Weihrauch and Gardner 1978). The main types of phytosterols found in legumes are β-sitosterol, campesterol, stigmasterol, and Δ5-avenasterol. Although phytosterols are absorbed through diet, their absorption is limited because they are actively

re-excreted by the body. Transporters like NPC1L1 help in their uptake, whereas ABCG5 and ABCG8 transporters push them back into the gut, resulting in low systemic absorption (Jukanti et al. 2012). Meanwhile, cooked pulses have a lower level of phytosterol. Specific legumes are particularly rich in phytosterols. Faba beans contain stigmasterol, β-sitosterol, and campesterol, which help lower cholesterol and reduce inflammation. Soybeans are a good source of Δ5-avenasterol, which supports brain and heart health. Horse gram provides essential phytosterols that contribute to enhancing heart health by lowering LDL cholesterol. β-Sitosterol is noted for its anti-inflammatory and anticancer properties, campesterol aids fat metabolism, and stigmasterol supports joint and skin health. Pigeon peas also offer high levels of phytosterols that help strengthen antioxidant defences, regulate fat metabolism, and relieve arthritis symptoms (Chaieb et al. 2011).

2.3 | Saponins

Saponins are natural compounds found in many plants, and the name comes from the Latin word *sapo*, meaning soap. Their molecular structure makes them both hydrophilic (water-attracting) and hydrophobic (water-repelling), allowing them to act like soap and create foam when mixed with water (Leon and Johanna 2018). Saponins are surface-active, nonvolatile compounds comprising a lipid-soluble aglycone (a sterol or triterpenoid) linked to sugar molecules. They are found in lentils, peas, black gram, lupin, and beans. Research shows that saponins possess a dual role in small to moderate amounts; they can provide health benefits like anticancer effects, lowering cholesterol, and boosting the immune system. But when their levels get too high, they can act as antinutrients (Saini et al. 2019). Their anticancer action involves stopping the cell cycle, blocking harmful cell activities, acting as antioxidants, and promoting programmed cell death (Elekofehinti et al. 2021). Saponins from pulses can boost resistance to cancers like cervical and colon cancer (Mudryj et al. 2014; Rochfort and Panozzo 2007). Pulse saponins exert their effects through various mechanisms, including immune modulation, influence on acid and neutral sterol metabolism, regulation of carcinogen-induced cell growth, and selective toxicity against cancer cells. Soybeans and chickpeas are major dietary sources of saponins. Soyasaponins from soybeans show anti-inflammatory, immune-boosting, anti-obesity, and liver-protective effects. Some types, like Saponin B1 and Soyasaponin II, even help fight HIV infection. Soyasapogenols have been found to slow tumor growth and help prevent colon cancer. They also show antioxidant, antidiabetic, antimutagenic, and cholesterol-lowering activities. Overall, saponins contribute to cancer prevention, protect the liver, and help manage blood cholesterol and sugar levels (B. Singh, Singh, Singh, et al. 2017).

2.4 | Carotenoids

Carotenoids are a type of terpenoid consisting of pigments responsible for different colors in plants and fruits. They are present in whole-grain cereals, and their class has naturally occurred in more than 600 tetraterpenoid organic pigments. These compounds are produced by plants, including algae and photosynthetic bacteria, and are commonly found in nature (Saini et al. 2019). The pigments responsible for the colors in these molecules range from yellow and orange to red in plants. They are valued for their antioxidant properties and role as provitamins. Carotenoids are generally divided into two groups: carotenes (α, β, and γ) and xanthophylls (astaxanthin, lutein, and zeaxanthin). Fruits and vegetables serve as the main dietary sources of these compounds. A deficiency can lead to various health issues, including xerophthalmia, night blindness, keratomalacia, corneal ulcers, and, in severe cases, permanent vision loss (Nissar et al. 2017). In pulses like lentils, chickpeas, and beans, carotenoids are present, although the levels tend to be lower compared to other sources like carrots, sweet potatoes, or spinach. Carotenoids are found in pulses, particularly in their leaves, and they have a possible role in cancer prevention and treatment. The content of pulse leaves is rich in carotenoids, including carotenes (primary component), lutein, neoxanthin, crocetin, antheraxanthin, violaxanthin, and other carotenoids in small quantities (Sri and Erdman 1987). Pulse roots contain fewer carotenoids than leaves. The various mechanisms through which carotenoids may control cancer development have been identified, such as antioxidant activities, retinol-related effects, and cell signalling (Fiedor and Burda 2014). The antioxidant properties of carotenoids help to reduce cancer risks, and specific carotenoids with anticancer potential include β-carotene, β-cryptoxanthin, lycopene, xanthophyll, zeaxanthin, and β-cryptoxanthin's role in regulating the expression of the RB gene, a recognised antioncogene (Horváth et al. 2021). The inclusive effects of pulse-derived carotenoids are defensive, preventive, and potentially therapeutic compared to several kinds of cancer (Nishino et al. 2000).

2.5 | Dietary Fiber

Pulse-based foods demonstrate substantial variability in dietary fiber content, influenced by species, variety, and processing methods. Among the pulses examined, bean pod flour is particularly remarkable, containing approximately 67% total dietary fiber (TDF) on a DW basis, dominated by insoluble fiber. Cooked black beans (23.4 g/100 g) and pinto beans (9 g/100 g) also provide considerable fiber, with navy beans delivering at least 20% of the daily value per serving. Cooking generally shifts fiber composition by increasing insoluble dietary fiber (IDF) and reducing soluble dietary fiber (SDF), as observed in black bean studies, with an overall 15%–30% TDF increase in some cases. Other pulses such as pigeon pea, horse gram, mung beans, rice bean, and cowpea show wide-ranging fiber levels. For instance, raw dried pigeon pea seeds contain 9.8–13 g/100 g fiber, whereas horse gram exhibits a wide spectrum, from about 5.3 g/100 g in whole seeds to nearly 29% in detailed compositional analyses. Similarly, mung beans range from 1.6% to 3.3% fiber in raw form to 7.6 g/100 g when cooked, and lentils, although reduced in density post-cooking, remain a rich fiber source at 7.9 g/100 g (N. Sharma et al. 2025).

Varietal diversity and targeted breeding also significantly influence fiber concentration. Rice bean and cowpea exemplify this, with rice bean values spanning from as low as 1.7% crude fiber to over 16 g/100 g in optimized genotypes, whereas cowpea seeds generally range from 11%–16% TDF but can reach over 21 g/100 g in select accessions. Both pulses show a predominance

of insoluble fiber, important for gastrointestinal health and metabolic regulation. In cowpea, cellulose constitutes nearly half of the fiber fraction, highlighting its potential for enhancing stool bulk and gut motility. Fresh or immature pods across species, such as cowpea green pods (3.3 g/100 g) or fresh pigeon pea pods (2–3 g/100 g), contain less fiber but still contribute to daily intake alongside other nutrients. Overall, these findings underline the dual role of pulses as both a dense fiber source in dry seed forms and a moderate contributor when consumed fresh, with cooking and processing offering additional modulation of fiber quality and quantity (Mallillin et al. 2008).

2.6 | Omega-3 Fatty Acids

Pulses such as common beans, pigeon peas, horse gram, mung beans, lentils, rice beans, and cowpeas display notable diversity in their omega-3 fatty acid content, particularly α-linolenic acid (ALA). Among them, *Phaseolus vulgaris* (common beans) stands out for having ALA as the dominant unsaturated fat, comprising about 43% of their total fatty acids, which translates to roughly 0.67 g per 100-g dry beans. Although beans are generally low in total fat, this high proportion means they can make a meaningful contribution to plant-based omega-3 intake, especially in diets low in fish or other direct sources of EPA and DHA. By contrast, pigeon peas (*Cajanus cajan*) contain only modest amounts—typically 20–40 mg ALA per 100 g when raw, dropping further with cooking—reflecting their lipid profile's strong bias toward omega-6 fatty acids. Horse gram (*Macrotyloma uniflorum*), despite its low total fat content (~2.3%–2.9%), provides a moderate 0.25- to 0.35-g ALA per 100 g, making it a nutritionally relevant, if secondary, omega-3 source (Choudhry 2012; Haji, Teka, Bereka, Andersa, et al. 2024; Longvah et al. 2017; J. P. Singh et al. 2021).

Mung beans (*Vigna radiata*), lentils (*Lens culinaris*), and rice beans (*Vigna umbellata*) tend to have smaller ALA contributions, although certain rice bean genotypes owing to higher overall lipid content (up to ~3.17%) and ALA dominance may approach 1- to 2-g ALA per 100 g, although precise data are lacking. Lentils offer only 37- to 100-mg ALA per 100 g, and mung bean sprouts just ~20 mg, but fermented mung beans can reach higher proportional ALA levels within their fatty acid profile. Cowpeas (*Vigna unguiculata*) bridge the gap, with 0.25- to 1.0-g ALA per 100 g depending on variety and growing conditions, because of their relatively higher lipid content (2.5%–3.3%) and variable ALA proportion (10%–30%). Overall, although none of these pulses match the ALA density of oilseeds like flax or chia, their role as accessible, affordable, and culturally integrated foods means they can collectively improve omega-3 intake in populations with limited access to marine or specialty plant oils (Choudhry 2012; Haji, Teka, Bereka, Andersa, et al. 2024; Longvah et al. 2017; J. P. Singh et al. 2021).

2.7 | Probiotics and Prebiotics

Across the studied pulses, a consistent theme emerges: Although they generally do not contain probiotics in their raw form, their complex carbohydrate profiles make them excellent prebiotic sources and suitable fermentation substrates. Species like *Phaseolus vulgaris*, *Lens culinaris*, and *Vigna unguiculata* are particularly rich in raffinose family oligosaccharides (RFOs), fructooligosaccharides (FOS), resistant starch, and amylose—compounds that resist digestion in the upper gastrointestinal tract and selectively stimulate beneficial gut bacteria such as Lactobacillus and Bifidobacterium. In many cases, a 100-g serving of these pulses can supply over half of the daily recommended prebiotic intake, contributing significantly to short-chain fatty acid (SCFA) production, improved gut microbiota balance, and reduced pathogenic bacterial populations. Lesser known pulses such as *Macrotyloma uniflorum*, *Vigna umbellata*, and *Cajanus cajan* also display promising prebiotic potential through resistant starch, galacto-oligosaccharides (GOS), and nonstarch polysaccharides, although their profiles are less extensively documented (Ashogbon et al. 2021; Choudhry 2012; Haji, Teka, Bereka, Astatkie, et al. 2024; Johnson and Thavarajah 2013; Longvah et al. 2017; J. P. Singh et al. 2021; Thavarajah 2012).

Fermentation emerges as a critical factor in unlocking the probiotic dimension of these pulses. Although raw seeds do not inherently harbor live probiotic microorganisms, controlled fermentation with lactic acid bacteria such as Lactiplantibacillus plantarum, *Lactobacillus acidophilus*, and Lacticaseibacillus rhamnosus not only introduces viable probiotic populations but also reduces antinutritional factors like α-galactosides, improving digestibility and enhancing nutrient bioavailability. Traditional fermented preparations, including tempeh-style beans, pickled cowpeas, and sprouted mung beans enriched with probiotics, illustrate culturally established methods of combining prebiotic substrates with live beneficial microbes. In these contexts, pulses function as effective carriers for probiotic survival, maintaining high cell counts during storage while simultaneously supplying fermentable carbohydrates that sustain bacterial activity (Granito et al. 2002; Kadyan et al. 2022; Longvah et al. 2017; Martín-Cabrejas et al. 2009; Martín-Cabrejas et al. 2008; Vidal-Valverde et al. 2002).

From a functional food perspective, these findings position pulses as dual-purpose ingredients in synbiotic formulations—products that combine both probiotics and prebiotics for synergistic gut health benefits. The rich and diverse carbohydrate content of pulses supports long-term microbiota modulation, whereas their compatibility with fermentation enables tailored probiotic delivery systems. This dual role is especially relevant for dietary strategies aimed at enhancing gut resilience, improving metabolic outcomes, and supporting digestive health in plant-based or resource-limited diets. Furthermore, the use of underutilized species such as rice bean and horse gram in fermentation technologies could expand the repertoire of affordable, culturally relevant synbiotic foods, making gut health interventions more accessible worldwide.

3 | Commodity-Based Recent Findings on Bioactive Components of Pulses and Their Therapeutic Potentials

In the literature, there are numerous studies on pulses, some of which are grown in India, such as chickpeas, kidney beans, horse gram, fava beans, soya beans, and pigeon peas, as shown in Table 2. The active phytochemicals prevent various diseases

TABLE 2 | Chickpea, horse gram, and kidney bean; different field studies.

Type of pulse	Year	Subject/focus	Bioactive compound studied	Observed health benefit or key finding	Study design/ methodology	References
Chickpea	2024	Antifreezing properties of pulse peptides	Peptides	Chickpea peptides effective as cryoprotectants	Antifreezing behavior tests, rheological analysis, and DPPH assay	(X. Zhu et al. 2024)
	2024	Foaming properties of pulse proteins	Globulins (vicilin, convicilin) and albumins	Lentil > chickpea > faba bean in foaming; vicilin key to performance	Alkaline extraction, SEC, and interfacial analysis	(Shen et al. 2024)
	2024	Chemical composition of chickpea varieties ("Costa 2004" and "El Patrón")	Phenols, globulins, and histidine	High antioxidant activity; "El Patrón" higher protein and fiber	Nutritional and antioxidant assays	(Pascual-Bustamante et al. 2024)
	2024	Biochemical traits of chickpea genotypes (71)	Protein, amino acids, and antioxidants	Identified genotypes with the highest protein (JG315) and antioxidants	Protein and amino acid profiling and DPPH assay	(Yadav et al. 2025
	2024	Composition of aquafaba from British Kabuli	Phenolics, saponins, and proteins	High phenolic and saponin content; potential food functional use	Centrifugation, TEM, SAXS, and SDS-PAGE	(Sahin et al. 2024)
	2022	Genome-wide mapping of nutritional traits	Protein, β-carotene, calcium, and folate	62 Genetic markers linked to key nutritional traits	GWAS on 258 accessions	(Roorkiwal et al. 2022)
Faba bean	2024	Mode of action of bioactive peptides	Antioxidant peptides and ACE-inhibitory peptides	Potent antioxidant and antihypertensive potential	In vitro digestion and molecular docking	(Martineau-Côté et al. 2024)
Kidney bean	2024	Effect of ultrasound on protein and antioxidant properties	Proteins, phenolics	↑ Protein recovery, solubility, emulsification, foaming, and antioxidants	Ultrasound treatment and DPPH and FRAP assays	(Yeasmin et al. 2024)
	2021	Acute vascular effects of beans vs. rice	Polyphenols and fiber (from beans)	Darker beans improved vascular function postmeal	Randomized crossover trial in healthy adults	(Clark et al. 2021)
	2022	Nutritional value and cardiovascular health benefits (review)	Phenolic acids, flavonoids, fatty acids	Cardioprotective effects: reduced cholesterol, blood glucose, lipid peroxidation, and inflammation	Literature review	(Clark et al. 2021; Rodríguez et al. 2022)
Horse gram	2022	Protein diversity analysis	Proteins	Identified protein profile clusters linked to grain color	1D and 2D gel electrophoresis	(N. Sharma et al. 2022)
	2020	Genetic diversity using SSR markers	Genomic SSR markers	Identified genetic groups and stocks for breeding	SSR marker development, clustering, and PCA	(R. Kumar et al. 2020)
	2024	Functional attributes of enzymatically derived protein hydrolysates	Protein hydrolysates (HG-PH)	Enhanced solubility, water/oil holding capacity, foaming capacity; potential food application	Enzymatic hydrolysis (Alcalase and Protex 6L); functional property analysis	(V. Sharma et al. 2024)

(Continues)

TABLE 2 | (Continued)

Type of pulse	Year	Subject/focus	Bioactive compound studied	Observed health benefit or key finding	Study design/ methodology	References
Mixed pulses	2024	Antifreezing properties of pulse peptides	Peptides (various pulses)	Chickpea peptides most effective	Same as chickpea study above (mixed pulses)	X. Zhu et al. 2024
Cowpea	2021	Nutritional quality, digestibility, and mineral bioavailability after fermentation	Proteins, essential amino acids, minerals (P, Mg, and K)	Fermentation improved protein/amino acid digestibility, P bioavailability, and reduced antinutritional factors; cowpea is a good protein and mineral source.	In vivo rat model; fermentation ± autoclaving; nutrient digestibility and mineral utilization assessment	(Sun et al. 2021)

and are investigated for their antioxidant, anti-inflammatory, antimicrobial, anticancer, and antidiabetic properties.

3.1 | Chickpeas

Chickpeas are a staple of pulses commonly eaten in Mediterranean and Western regions. They consist of essential nutrients such as dietary fiber, vitamins, minerals, and antioxidants, all of which contribute to a healthy body. Chickpeas also include bioactive substances such as flavonoids, phenolic acids, and bioactive peptides, which have antioxidant, anticancer, and blood pressure-lowering effects. Nondigestible carbohydrates, including compounds like dietary fiber, resistant starch, carotenoids, and phytosterols, can help manage diabetes, obesity, cancer, osteoporosis, and heart disease (Brownlee 2011; Didinger et al. 2022).

3.1.1 | Nutritional Compositions of Chickpea and Their Health Benefits

According to USFDA (2023), analysis of chickpeas reveals significant nutritional content, particularly in carbohydrates and minerals. The total carbohydrates per 100 g were found to be 60.4 g, with 34.1 g of starch. Chickpeas provide essential minerals rich in calcium (111 mg), iron (5.09 mg), magnesium (135 mg), and potassium (1070 mg), which support bone health, heart function, and oxygen transport. Additionally, they contain 3.12 mg of zinc, 0.804 mg of copper, and 3.58 mg of manganese, supporting immune function and overall metabolism. These pulses' high antioxidant capacity is attributed to their phenolic compounds, flavonoids, and tocopherols. The generation of hydrogen atoms by cellular oxidation is the best example of suppressing DNA, protein, and lipids (Amarowicz et al. 2010; B. Singh et al. 2016). Oxidative stress is caused by several disease conditions, such as cancer, obesity, neuronal disorders, cardiovascular disorders, and diabetes (Forman and Zhang 2021; Sharifi-Rad et al. 2020). Chickpeas have been shown to possess anti-inflammatory characteristics. The therapeutic effect of desi chickpea extract was observed to inhibit prostaglandin E2 (PGE2) synthesis by around 85%. PGE2 is a lipid compound that acts as a hormone secreted by blood vessel walls in response to inflammation or infection. In the animal study, BALB/c male mice with aorta were fed chickpeas instead of 20% of their regular diet. This dietary change suggests chickpeas could be used as nutraceuticals (foods with health benefits) in postmenopausal conditions. This research highlights the potential of chickpeas as a functional food, particularly for their anti-inflammatory effects and possible benefits in postmenopausal conditions (Mathew et al. 2022). Chickpea seeds exhibit notable antimicrobial properties. Despite a minimum inhibitory concentration (MIC) ranging from 16 to 64 μg/mL, their extract shows significant anti-bacterial activity against a variety of harmful (−ve) strains such as *Escherichia coli*, *Klebsiella pneumoniae*, and *Pseudomonas aeruginosa*. It is efficient toward *Enterococcus faecalis* and has antifungal activity against *Candida albicans* at a concentration of 8 μg/mL for positive (+ve) (A. Kan et al. 2010). The lectin compound from chickpeas was also reported to have significant antifungal

effects, reducing the growth of *Candida krusei* by 85% and *Fusarium oxysporum* by 81%. Moreover, it has been found that chickpeas also inhibit *Saccharomyces cerevisiae* and *Candida albicans*(Gautam et al. 2018). In addition to these properties, components of chickpea seed extract, such as cineraria and specific peptides, have been observed to inhibit HIV-1 reverse transcriptase (Barbosa et al. 2021).

3.1.2 | Antioxidant and Anti-Inflammatory Compounds Present in Chickpeas

Chickpeas contain important nutrients and bioactive compounds that provide antioxidant and anti-inflammatory effects. These properties help lower the risk of chronic illnesses like heart disease, diabetes, and cancer. An investigation of physicochemical properties and bioactive compounds on germinated black chickpeas (*Cicer arietinum*) was performed by Shahid et al. (2024). The study showed that as germination time increased, the overall nutrient and phytochemical content also increased. However, the levels of certain compounds, such as rutin, luteolin, kaempferol, and quercetin, gradually decreased during germination, and the amount of isorhamnetin rises with the time of germination (Figure 2). The antioxidant assay was performed using DPPH and ABTS methodologies. Bochenek and colleagues explored the potential of chickpea water (aquafaba) as a source of bioactive compounds with antioxidant and anticancer properties. The study revealed that germinated chickpeas (BG1) contained the highest levels of antioxidant compounds compared to nongerminated ones (BG2). The ability of extract to neutralize free radicals was assessed using DPPH and ABTS tests, and it was found that chickpea polyphenol extract (CPPE) had an antioxidant activity of 22.2-mg/g TE. Chickpea powder (CPW) had an activity of 8.41 mg/g TE. CPPE showed significantly higher antioxidant activity, especially in the DPPH test. For the ABTS test, CPW had 29.65-mg/g GAE, and CPPE had 25.06-mg/g GAE, with CPW showing slightly higher activity (Bochenek et al. 2023).

Both CPPE and CPW were also tested for their anticancer potential using an in vitro model against various cancer cell lines, including CRC, SW480, and HT-29 cell lines. The results showed that CPPE and CPW could affect cancer cell growth, death, movement, and spread. The chemical analysis of total phenolic compounds (TPC) revealed polyphenols in CPW, although in lower amounts than in CPPE. Despite this, CPW showed similar antioxidant activity to CPPE, especially in the ABTS test. The most active bioactive compounds in these extracts were rutin and gallic acid, which are known for their potent antioxidant properties.

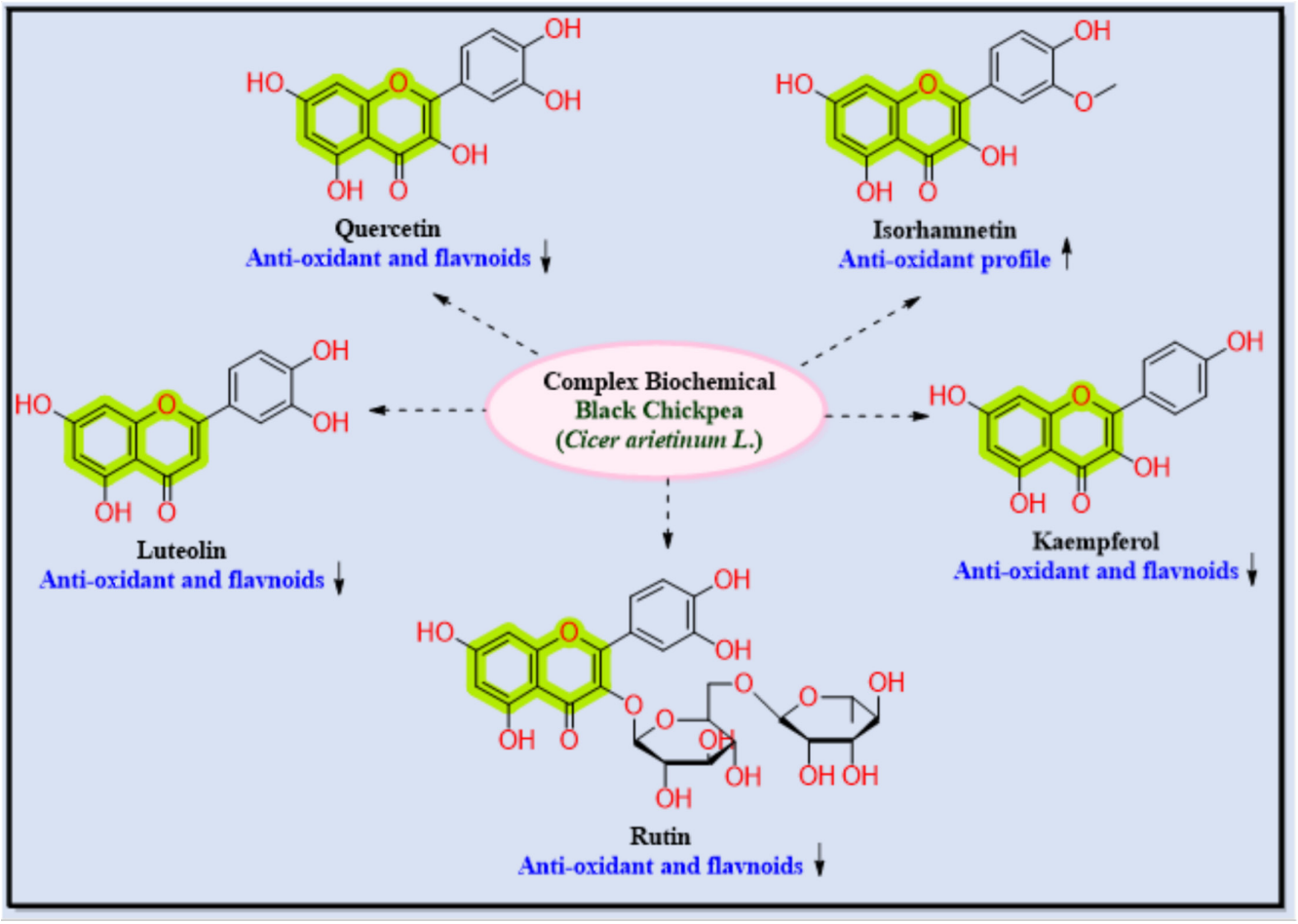


FIGURE 2 | Reported biochemical structure of black chickpeas and their antioxidant profiles. (quercetin, luteolin, rutin, isorhamnetin, and kaempferol).

Recent research has shown an interest in chickpea water, also known as aquafaba. The CPW, or aquafaba, is the liquid leftover from cooking chickpeas. Echeverria-Jaramillo et al. 2021 analyzed growing interest in CPW, especially in the vegan community. The primary use is being explored as an egg replacer because of its foamy and blending properties (Echeverria-Jaramillo et al. 2021).

In 2024, Felisiak and their colleagues investigated chickpea flour's increased bioactive compounds and antioxidant effect instead of wheat flour for shortbread (Felisiak et al. 2024). This study found that adding chickpea flour to shortbread cookies significantly enhanced their bioactive compound content, particularly polyphenols and flavonoids. Cookies made entirely with chickpea flour (S100) had 2.5 times more polyphenols than those made with wheat flour. Similarly, flavonoid levels increased from 0.5- to 26.5-μg QE/g as the proportion of chickpea flour rose. This increase in bioactive compounds improved the cookies' antioxidant properties, with Trolox equivalent antioxidant capacity (TEAC) increasing five times and DPPH radical scavenging activity rising six times. In the same year, 2024, according to Huang et al., studies engineered plants to produce bioactive oligosaccharides and peptides in human milk (Huang et al. 2024). The bioactive compounds in chickpeas and standard beans are present in their cooking water, known as aquafaba. Researchers used high-performance anion exchange chromatography to identify and quantify oligosaccharides like stachyose, raffinose, and verbascose in chickpeas. LC-MS/MS techniques also revealed 78 oligosaccharides in chickpeas and 67 in common beans. The study analyzed the protein and carbohydrate content in aquafaba; analysis showed that chickpea aquafaba contained 23.8–31.5 mg/mL of protein and 6.2–11.5 mg/mL of carbohydrates, whereas common bean aquafaba had higher carbohydrate levels (30.1–40.0 mg/mL) and lower protein levels (4.1–7.2 mg/mL). Additionally, the research identified several γ-glutamyl peptides in both chickpeas and beans, which contribute to the kokumi taste and have anti-inflammatory properties. Notably, γ-Glu-Phe was found in chickpeas, whereas γ-Glu-Leu was present in beans, both showing potential health benefits.

3.1.3 | Chickpea Anticancer Properties

Bochenek et al. (2022) performed an in vitro study to observe the bioactivity of chickpeas against colon cancer progression in the HT-29 cell line (Bochenek et al. 2022). This study evaluated the biological effects of CPW and CPPE to determine their impact on colorectal cancer development. Various tests, including cell viability assays, a cell migration scratch test, and apoptosis analysis, were used to measure their impact. Both CPW and CPPE significantly reduced the viability of HT-29 colon cancer cells at concentrations of 50 μg/mL and higher. At increased concentrations (250 and 500 μg/mL), both extracts induced noticeable apoptosis compared to untreated cells. Additionally, CPW decreased cell migration by 34.42%, whereas CPPE reduced it by 15.27%, suggesting that CPW was more effective in limiting metastasis. In vitro analysis showed that both CPW and CPPE demonstrated comparable antioxidant and anticancer effects. Another study conducted by Domínguez-Arispuro Dulce-María and coworker on the effects of unfermented chickpea flour (UCF) and sprouted chickpea flour (SCF) on the HepG2 liver cancer cell line focused on their antioxidant and cytotoxic properties. The findings showed that sprouting significantly increased the antioxidant activity of the chickpea extracts. SCF had a much higher antioxidant activity (222.2-μmol QE/100 g) compared to UCF (41.2-μmol QE/100 g), especially when using a PBS wash protocol. After sprouting, the antioxidant activity of SCF increased almost five times compared to UCF. EC_{50} values, which measure the effectiveness of a substance, dropped sharply from 28 mg/mL for UCF to 5.1 mg/mL for SCF, indicating stronger effects after sprouting. When no PBS wash was used, the antioxidant activity of SCF improved by about 470%, and its EC_{50} value decreased significantly from 4.91 to 0.88 mg/mL. The cytotoxic effects were confirmed through cell membrane damage, observed using a staining protocol, where SCF caused more severe damage than UCF, including fragmented nuclei. Both UCF and SCF showed cytotoxicity, although it was unclear if the extracts caused cell death through apoptosis. In breast cancer cells, UCF reduced cell viability at higher doses (1–15 mg/mL), whereas SCF showed a dose-dependent effect with an IC_{50} value of 11 mg/mL. Additionally, both extracts affected normal NIH-3T3 fibroblast cells, with significant differences between the unsprouted and sprouted extracts. The highest dose of UCF (15 mg/mL) did not determine an IC_{50} value in either cancerous or normal cells. These results indicate that both UCF and SCF can reduce cancer cell growth, with SCF demonstrating stronger antioxidant and cytotoxic effects after sprouting (Dulce-María et al. 2021). Wang and their colleagues investigated the antiproliferative effects on the human breast cancer cell line (MCF-7) using isoflavone extract from chickpeas and concentrations ranging from 10 to 60 μg/mL. The MTT assay demonstrated that chickpea isoflavones significantly inhibited MCF-7 cell proliferation in both a time-dependent and dose-dependent manner. The calculated IC_{50} value for chickpea isoflavones after 48 h of treatment was 32.8 μg/mL. Flow cytometry analysis revealed a dose–effect relationship, with the highest apoptosis rate occurring at a dose of 60 μg/mL, which was significantly different from the control group ($p < 0.01$). Further examination of the MCF-7 cells showed that chickpea isoflavones led to noticeable changes in cell morphology. Although control cells (treated with DMSO) exhibited normal, adherent growth with uniform size and shape, the treated cells appeared shrunken and round, with reduced cell density, irregular morphology, concentrated chromatin, and vacuolar-like changes in the cytoplasm. These findings suggest that chickpea isoflavones effectively inhibit breast cancer cell proliferation and induce apoptosis, making them a promising potential therapeutic agent in breast cancer treatment (J. Wang et al. 2020).

3.2 | Kidney Beans

Kidney beans (*Phaseolus vulgaris*), a variety of common bean, are recognized for their unique kidney shape and deep red color. They are widely consumed worldwide and are valued for their nutritional content. The macronutrient analysis of dark red kidney beans by the USFDA (2016) revealed important nutritional content. They contain 4.3 g of dietary fiber per 100 g, with 36.7 g of starch. The mineral content includes calcium (98 mg), iron (6.58 mg), magnesium (164 mg), and phosphorus (612 mg). Dark red kidney beans are also rich in

1490 mg of potassium and provide 3.29 mg of zinc, 0.865 mg of copper, and 1.67 mg of manganese. Other trace elements include 241 mg of sulfur, 79 μg of nickel, 572 μg of molybdenum, and 30 μg of cobalt. Lastly, dark red kidney beans also contain 1100 μg of boron (Shevkani et al. 2015). The phytochemicals of kidney beans contain phenolic compounds such as flavonoids, tannins, and phenolic acids, which play a key role in their antioxidant properties, as illustrated in Figure 3. They also contain antinutritional compounds (ANCs) such as lectins, phytic acid, trypsin inhibitors, oligosaccharides, and resistant starch.

3.2.1 | Antioxidant Potential of Kidney Beans

Rostkowska et al. (2024) investigated the phytochemical composition in micellar extract from kidney beans (Rostkowska et al. 2024). This study identified 32 chemical compounds in red kidney beans, including phenolic acids, flavanols, flavan-3-ols, flavanones, and isoflavones. Also, other key compounds detected were hyperoside, quercitrin, ferulic acid, caffeic acid, and rutin. The biological effects of these compounds were examined for cytotoxicity, anti-inflammatory, antioxidant, anticollagenase, antielastase, antityrosinase, and collagen synthesis activities. The

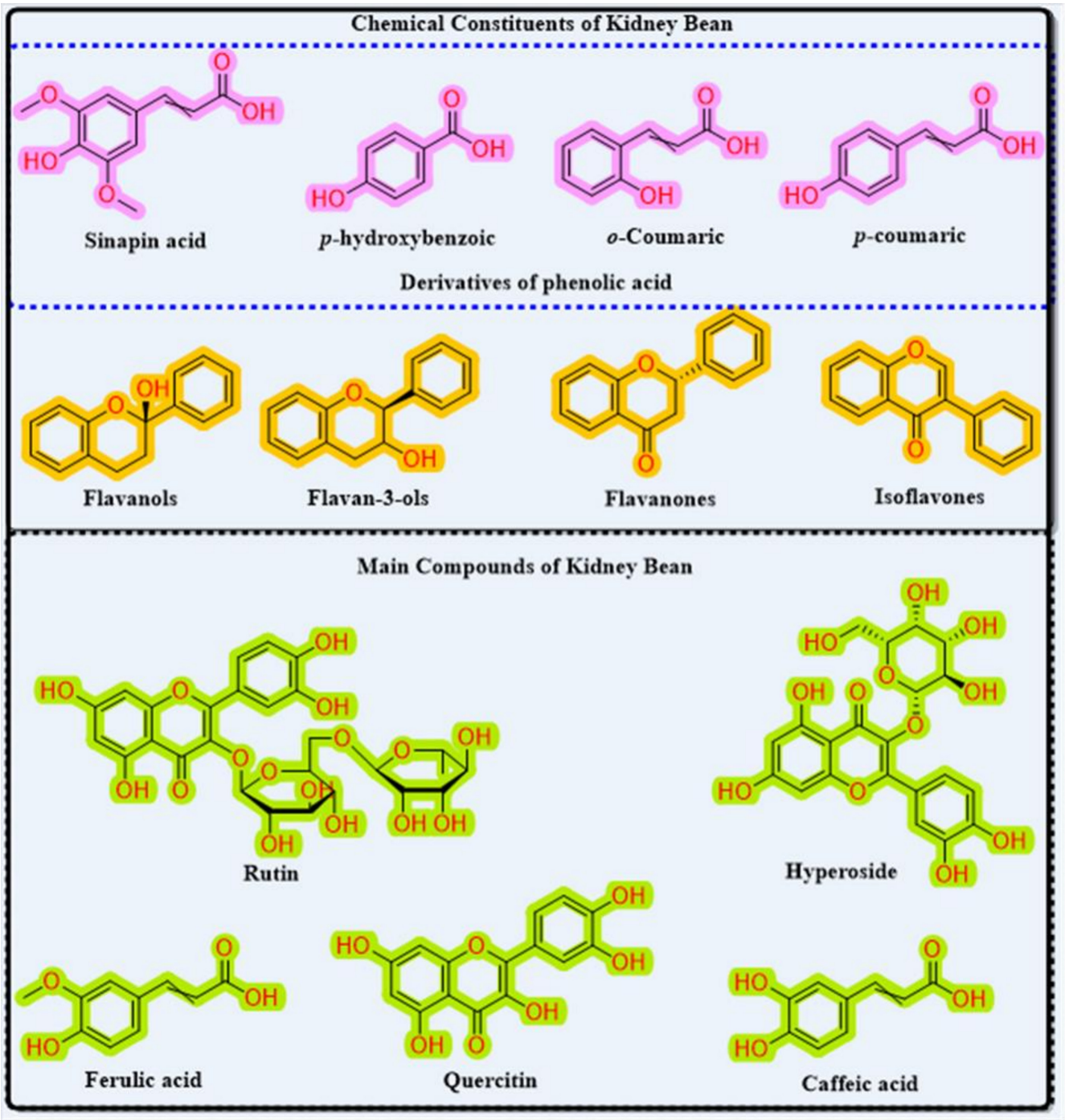


FIGURE 3 | Chemical constituents of kidney bean, sinapin acid, *p*-coumaric, flavanols-4, flavanones, isoflavones, flavan-3-ols, *p*-hydroxybenzoic, and *o*-coumaric (derivatives of phenolic acid). The main compounds are rutin, hyperoside, ferulic acid, caffeine, and quercetin.

antioxidant potential of common bean sprout micellar extract was assessed using DPPH and ABTS•+ assays in a microplate-based, cell-free system. The findings showed antioxidant activities of 246.24-mg Trolox/g DE in the DPPH assay and 74.38-mg Trolox/g DE in the ABTS assay.

L. Zhu et al. (2024) have highlighted the efficiency and effectiveness of extraction with ultrasound assistance to obtain free phenols from kidney bean seeds. Sequential hydrolysis methods used alkali-acid and acid-alkali treatments were found to be more efficient in releasing bound phenols from the seed coat and cotyledons, respectively. Under optimized conditions, total phenolic content (TPC), flavonoid content (TFC), and anthocyanin content (TAC) in five kidney bean cultivars ranged from 7.81- to 32.89-mg GAE/g dw, 3.23- to 15.65-mg RE/g dw, and 0- to 0.21-mg CE/g dw, respectively. Antioxidant potential was assessed using DPPH, ABTS, and FRAP assays, revealing that the seed coats of red cultivars exhibited stronger antioxidant activity than the cotyledons. The SF cultivar showed the highest antioxidant activity, followed by bound phenol extracts from the seed coat. In contrast, free and bound phenol extracts from the cotyledon exhibited lower antioxidant activity, with minimal differences except for DPPH in the "British Red" and "Yikeshu" cultivars. The strongest antioxidant activity was observed in the combination of SBC + SB-AC extracts for the white "Sark" variety. Interestingly, CF and (CAC + CA-BC) extracts displayed greater antioxidant potential than SF, despite differences in total phenol content. Overall, the "Zhuhong" cultivar exhibited the highest total antioxidant capacity in whole seeds, followed by "British Red," "Yikeshu," "Japanese Red," and "Sark." The highest antioxidant activity in cotyledons was found in "British Red," whereas "Zhuhong" showed the highest antioxidant activity in bound phenol extracts (L. Zhu et al. 2024).

3.2.2 | Anticancer and Antimicrobial Activities of Kidney Beans

In 2023, Elbadrawy and Mostafa (2024) conducted a study on the methanolic extract of broad bean pods. The study showed that the antioxidant activity of broad bean pod extract increased with concentration, reaching 80.5% at 1000 μg/mL, indicating strong antioxidant potential. The extract also demonstrated significant reducing power and free radical–scavenging effects, with an IC_{50} value of 87.35 μg/mL. In antimicrobial tests, it effectively inhibited the growth of bacteria such as *Bacillus subtilis*, *Staphylococcus aureus*, *Escherichia coli*, and *P. aeruginosa* while also exhibiting antifungal activity against *Candida albicans*. However, no inhibitory effect was observed against *Aspergillus fumigatus*. The extract also showed anticancer potential by significantly reducing the viability of human liver cancer (HepG2) and prostate cancer (PC3) cells, demonstrating strong cytotoxic effects at higher concentrations. These findings suggest that broad bean pod extract, rich in phenolic compounds, may serve as a natural antioxidant and anticancer agent.

Additionally, in vitro studies conducted by Herrera and colleagues confirmed the antioxidant and anti-inflammatory activity of L-DOPA and compounds derived from bean plants. The plant extracts showed strong radical capture activity, with the highest inhibition observed at a concentration of 200 μg/mL, reaching about 80% after 10 min. Among the broad bean varieties tested, Rojita exhibited the strongest antioxidant activity with an IC_{50} of 87.68 μg/mL, significantly outperforming other varieties like José María and Matlazinca. The strong antioxidant effect of broad bean extracts is likely due to their high L-DOPA content, which has been linked to antioxidant properties. When it comes to anti-inflammatory effects, all the extracts showed similar trends, with Rojita again leading the way, showing 76% inhibition at a concentration of 150 mg/mL. The IC_{50} for Rojita was 74.40 mg/mL, lower than that of the anti-inflammatory drug diclofenac sodium. The anti-inflammatory action is believed to be related to the flavonoid content in the plant, which is most abundant in the plants at 20 days after emergence (DAE) (Fuentes-Herrera et al. 2023).

Une et al. (2024) investigated the antiproliferative and anti-inflammatory effects of boiled kidney beans of crude lectins (Une et al. 2024). The antiproliferative activity of raw and boiled bean lectins was exhibited against five cancer cell lines (B16, LM8, HeLa, HepG2, and Colo679), as shown in Figure 4. They found that lectins extracted from boiled red kidney beans were found to significantly reduce the expression of inflammatory markers, including tumor necrosis factor-alpha (TNF-α) and interleukin-6 (IL-6). These results indicate that lectins from red kidney beans may have potential anti-inflammatory properties. Notably, these bioactive properties remain intact even after heating, indicating that cooked beans may still offer health benefits.

3.3 | Horse Gram

The *Macrotyloma uniflorum* is also known as horse gram or gaeth. The horse gram is a lesser known pulse with several interesting properties and benefits. The nutritional profile of these pulses is high in protein and rich in iron, calcium, and other minerals. They are also a good source of dietary fiber. The health benefits of horse gram are that it may help regulate blood sugar levels and contain antioxidants (Bhartiya 2015).

3.3.1 | Antioxidant Properties of Horse Gram

Mathaiyan and co-workers evaluated the antioxidant, anticancer, and hepatoprotective effects of horse gram seed (Mathaiyan et al. 2023). The methanol extract of *Macrotyloma uniflorum* (horse gram) seeds exhibited strong free radical scavenging activity. The antioxidant potential of the methanol extract of horse gram was tested against different free radicals, including DPPH, hydroxyl (OH), ABTS, and FRAP. The findings revealed that the extract had strong DPPH free radical scavenging activity, reaching 93.5% at a concentration of 100 mg/mL, which was nearly as effective as ascorbic acid. The IC_{50} value for DPPH was 41.524 mg/mL, suggesting significant antioxidant potential. The methanolic extract also demonstrated moderate scavenging activity against OH and ABTS radicals, with lower efficiency than positive controls like catechin and ascorbic acid. Interestingly, the extract had notable ferric-reducing potential, with a 95.52% reduction at the highest dose. The cytotoxicity study indicated dose-dependent activity against HepG2 cancer

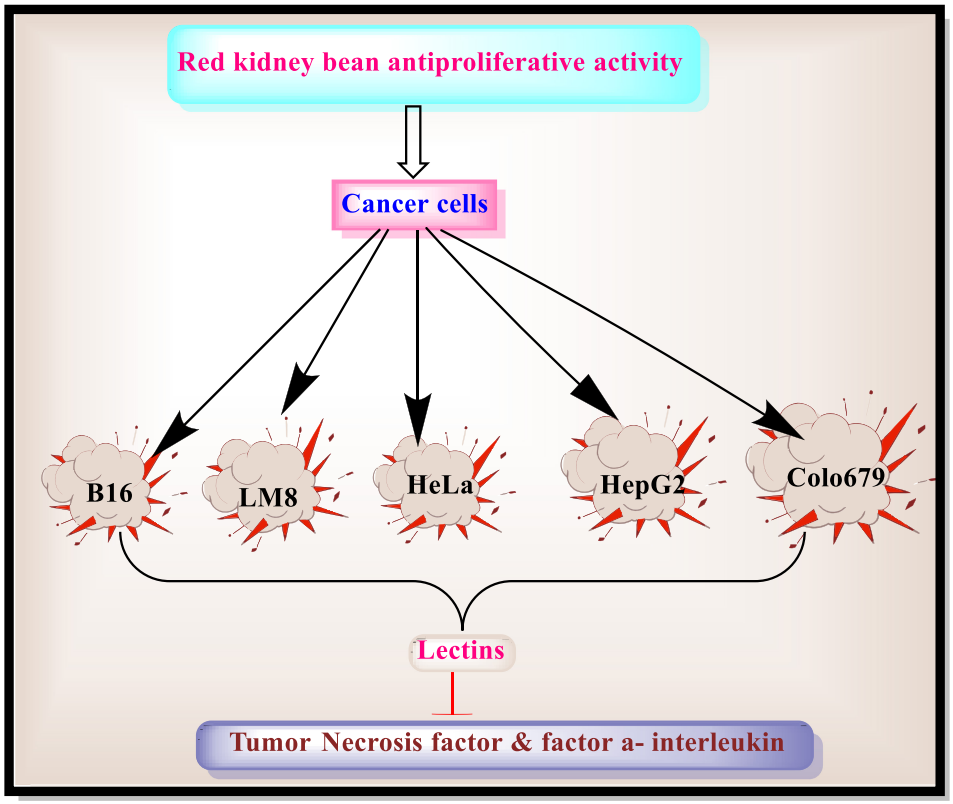


FIGURE 4 | The antiproliferating activity of red kidney bean against cancer cells, that is, B16, LM8, HeLa, HepG2, and Colo678.

cells, with an IC_{50} of 180.11 mg/mL. Furthermore, the extract displayed protective effects against nephrotoxicity and hepatotoxicity in cell models.

A study by Rehman *et al*. in 2021 compared the sprouts vs. seeds of two pulse species: *M. uniflorum* and *V. radiata*. This study examined the antioxidant capacity of methanol-based extracts from these pulses' seeds and sprouts. The study assessed the antioxidant activity of methanol extracts obtained from the seeds and sprouts of two different pulses: *Vigna radiata* and *M. uniflorum*. Using DPPH, the study determined the IC_{50} values, which show how much extract is needed to inhibit 50% of free radicals. The results indicated that sprouted *M. uniflorum* exhibited the highest antioxidant activity, followed by sprouted *V. radiata*, *M. uniflorum* seeds, and *V. radiata* seeds. For total antioxidant capacity, measured using ascorbic acid equivalents, sprouts consistently showed higher antioxidant values compared to seeds. This indicates that sprouting increases the antioxidant potential of the pulses. The overall ranking, based on various antioxidant assays, placed sprouted *M. uniflorum* as the most potent, followed by sprouted *V. radiata*, *M. uniflorum* seeds, and *V. radiata* seeds. These findings support the idea that sprouting enhances the nutritional value of pulses, potentially offering greater health benefits due to higher antioxidant activity, which may help prevent chronic diseases like cancer and heart disease (Rehman et al. 2011).

A study on the antioxidant properties of an ethanolic leaf extract of *M. uniflorum* was performed by Kaundal et al. (2019). The ethanolic seed extracts of *M. uniflorum* (horse gram) show promising antioxidant activity in various studies. In one experiment, the extracts improved antioxidant enzyme levels such as superoxide dismutase, catalase, and glutathione concentration in rabbits. Researchers evaluated both raw and heated seed samples using methanol and 70% acetone, assessing their ability to scavenge different free radicals like α, α-diphenyl-β-picrylhydrazyl (DPPH), ferric reducing antioxidant power (FRAP), and hydroxyl radicals. The 70% acetone extract demonstrated the highest scavenging activity, especially for hydroxyl radicals. Overall, all extracts displayed strong antioxidant properties. Further, in vitro studies showed that horse gram leaf extracts were effective in scavenging various free radicals, which are crucial in managing diseases like diabetes. The maximum DPPH radical scavenging activity reached 55%, whereas other radical activities like ABTS, hydroxyl, and nitric oxide scavenging showed high percentages. In addition, the antioxidant potential of horse gram was confirmed in seed coat extracts, which also exhibited protective effects against skin cancer cells. Moreover, when rats were fed boiled and unboiled horse gram for 21 to 60 days, their antioxidant enzyme activities improved significantly. These findings highlight the potential of horse gram as a natural source of antioxidants with therapeutic applications (Kaundal et al. 2019).

3.3.2 | Anti-Cancerous Activity of Horse Gram

A study conducted by Chakraborty and their colleagues (Chakraborty et al. 2018) on the medicinal properties of *M. uniflorum* found that the anticancer activities of four samples were tested and compared to the standard drug, cisplatin, and a controlled solvent (DMSO). The research focused on the B16F10 and B16BL6 skin cancer cell lines. Sample 1 exhibited no cytotoxic effects, whereas Sample 3 displayed significant cytotoxic

activity against both cell lines. The cytotoxicity of Sample 3 was 41% at 500 μg/106 cells and 64% at 100 μg/106 cells, which was higher than cisplatin (32.01% at 500 μg/106 cells). Samples 2 and 4 also showed effective cytotoxic activities. When stained with acridine orange and examined under a fluorescence microscope, Sample 1 showed no toxic effects, whereas Sample 3 exhibited the highest cytotoxic activity, followed by Samples 2 and 4. Additionally, *M. uniflorum* seeds were tested against the human osteosarcoma MG 63 cell line, where methanol and ethanol extracts demonstrated cell viability of 82% and 74%, respectively. The findings confirm that the seed coat of *M. uniflorum* possesses significant anticancer potential against B16F10 and B16BL6 melanoma cell lines.

The study was conducted by Ramasamy *et al*. (Ramasamy et al. 2017) to investigate the hepatoprotective (liver-protecting) effects of certain plant extracts on rats with induced liver toxicity. The Wistar albino rats were used as the animal model, and in this study, they showed that paracetamol (acetaminophen) was administered orally for ten days to induce liver toxicity. The results demonstrated that both ethanol-based and water-based extracts improved biochemical indicators in rats with liver toxicity. The improvements were comparable to those seen with silymarin. The ethanolic extract showed superior therapeutic efficacy. The phytochemical analysis revealed abundant plant-based compounds (phytoconstituents), such as phenolic compounds, flavonoids, and alkaloids. The presence of these phytoconstituents is believed to contribute to the hepatoprotective action of the extract. This study suggested that the plant extract, particularly the ethanol-based version, has potential as a treatment for liver damage, possibly due to the presence of specific plant compounds.

3.3.3 | Anti-Inflammatory Properties of Horse Gram

Vasishta et al. (2021) studied (Vasishta et al. 2021) an ethanolic plant extract to investigate its potential medicinal properties in vitro. The study focused on free radical scavenging activity and anti-inflammatory activities of horse gram. The study's key findings were the ethanolic extract containing polyphenolic compounds, particularly tannins and flavonoids. These molecules exhibited strong antioxidant properties in laboratory tests. The plant exhibited strong anti-inflammatory properties by reducing the production of important inflammatory molecules, including NO, PGE2, IL-6, IL-1, TNF, and MMPs. These results suggest that the plant could be useful in developing anti-inflammatory therapies. Additionally, it showed potential anti-diabetic and anti-urolithiasis effects (Patel and Achaarya 2020).

This study by Sudha *et al*. (Sudha and Saral 2023) examined *M. uniflorum* flour and its extracts as a mineral-rich source with antidiabetic and anti-urolithiasis properties. It also compared these extracts with biosynthesized silver nanoparticles (HG-AgNPs). The research analyzed the growth of struvite crystals at different extract and HG-AgNP concentrations, identifying three crystal morphologies: needle-shaped, X-shaped dendritic, and feather-like. Both the extracts and HG-AgNPs inhibited struvite crystal formation, with HG-AgNPs showing a stronger effect. Additionally, the study assessed antidiabetic potential by evaluating α-amylase enzyme inhibition, an important target in Type 2 diabetes management. HG-AgNPs demonstrated a more potent, dose-dependent inhibitory effect, with the highest activity at 100 μg/mL.

3.4 | Pigeon Peas

Pigeon peas, also known as tropical green peas or Congo peas, are a nutritious pulse with several health benefits. Pigeon peas are an excellent natural source of plant-based protein. They contain high amounts of dietary fiber, which supports digestion and gut health. Additionally, they are rich in B-complex vitamins, particularly folate, and provide essential minerals such as iron, magnesium, and potassium. They also contain antioxidants that may help reduce inflammation and oxidative stress, provide sustained energy, and help regulate blood sugar levels (Sarkar et al. 2020). The bioactive compound is shown in Figure 5.

3.4.1 | Antioxidant Activity of Pigeon Peas

Nehra and colleagues investigated the use of pigeon pea pod coat as a natural antioxidant to enhance the stability of crude

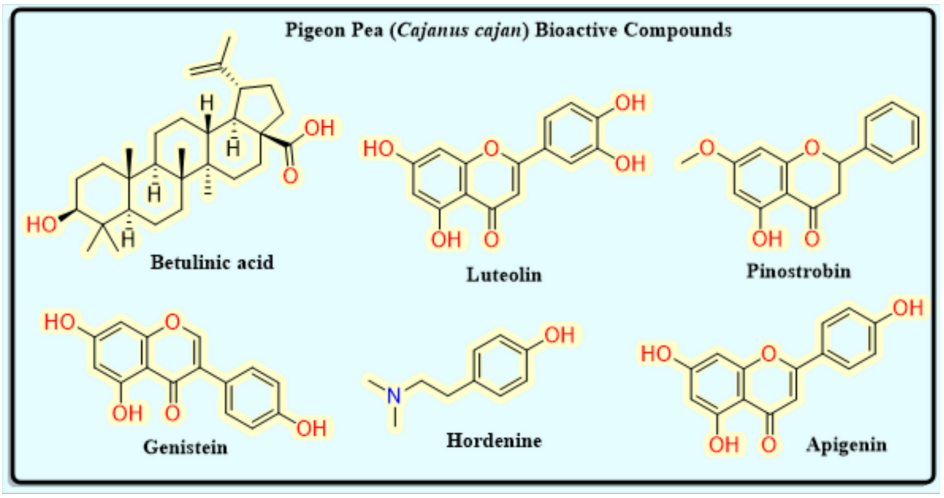


FIGURE 5 | Reported pigeon peas' different bioactive compounds: betulinic acid, luteolin, genistein, apigenin, hordenine, and pinostrobin.

soybean oil stored at 50°C for 28 days. Among the solvents used, acetone produced the highest extract yield (4.88 g per 100 g), followed by ethyl acetate and chloroform. The acetone extracts also contained the highest levels of total phenolics, flavonoids, and tannins. Its strong antioxidant activity was demonstrated by a DPPH free radical scavenging rate of 78.21%. The study found a strong correlation between phenols, flavonoids, and tocopherols, all contributing to the antioxidant power. The FTC method confirmed acetone's superior performance, with a 68.22% inhibition of lipid peroxidation, further supporting its potential as an effective natural antioxidant (Nehra et al. 2021). J. Mukherjee et al. (2024) evaluate the antioxidant capacity of pigeon pea samples using the DRSA method, which is known for its simplicity and effectiveness. The results showed that enzymatic hydrolysis of pigeon peas led to the highest antioxidant activity, with an 80% scavenging capacity, followed by acid hydrolysis, defatted, and unhydrolyzed samples. This increase in antioxidant activity with hydrolysis is consistent with other studies, which show that hydrolysis exposes more hydrophobic side chains, enhancing antioxidant potential. The study observed a direct relationship between phenolic content and antioxidant activity. Since phenolic compounds can neutralize free radicals, they help in reducing oxidative stress. Additionally, the hydroxyl radical scavenging ability (HRSA) of the hydrolyzed samples showed a similar trend, with enzymatic hydrolysis yielding the highest scavenging ability. The reducing power of the hydrolyzed samples, particularly acid and enzymatic hydrolysates, also demonstrated strong antioxidant activity, which is crucial for neutralising free radicals. These results suggest that pigeon pea hydrolysates could serve as effective natural antioxidants (S. Mukherjee et al. 2022). Haji et al. studied how traditional processing methods influence the nutritional value and antioxidant properties of pigeon pea flour. It was found that most processing methods reduced the total phenolic and flavonoid content, as well as antioxidant activity, except for germination, which significantly enhanced these properties. Germination enhanced the levels of total phenols and flavonoids, leading to a higher DPPH radical scavenging capacity, which suggests improved antioxidant potential. In contrast, soaking, cooking, and roasting reduced antioxidant activity, likely due to heat-induced degradation and the loss of bioactive compounds into the water. Germination also led to a notable increase in FRAP values, suggesting that it enhances the antioxidant capacity of pigeon pea. The IC_{50} values, which measure the antioxidant effectiveness, revealed that germinated pigeon pea flour had the lowest IC_{50}, indicating the highest free radical scavenging ability (Haji, Teka, Bereka, Astatkie, et al. 2024).

3.4.2 | Antimicrobial and Antioxidant Properties of Pigeon Peas

Orni et al. (2018) investigated hydrolyzed pigeon pea proteins and evaluated the antimicrobial and antioxidant properties of bioactive compounds present in pigeon pea roots. The pigeon pea proteins were hydrolyzed using three enzymes: pepsin, trypsin, and papain. The antimicrobial activity was evaluated, and varying degrees of antimicrobial activity were observed. The papain hydrolysates exhibited the widest range of activity, effectively inhibiting four bacterial strains: *Staphylococcus aureus, Acinetobacter baumannii*, *Escherichia coli*, and *Salmonella* spp. The antioxidant properties were evaluated using the DPPH free radical scavenging assay and the FRAP assay, which measures ferric ion-reducing antioxidant power. The tryptic digestion hydrolysates showed the highest antioxidant activity in both assays. They revealed that enzymatically digested pigeon pea proteins could yield peptides with potential use in formulating novel treatments for infectious diseases (Orni et al. 2018).

In recent years, in 2024, Ekun et al. investigated the pigeon pea seed protein hydrolysates and their antimicrobial and antioxidant properties (Ekun et al. 2024). They highlighted the potential of pigeon pea based on bioactive peptides with beneficial health effects. The preparation method they used was pigeon pea-dried seed, crushed, and stored at 10°C in an air-tight container. Proteins were broken down using three enzymes: pepsin, trypsin, and papain. The antimicrobial effects were tested against seven bacterial strains, including *Escherichia coli*, *Staphylococcus aureus*, *Enterobacter cloacae*, *Klebsiella pneumoniae*, *Acinetobacter baumannii*, *Vibrio* spp., and *Salmonella* spp., with levofloxacin as the control. All hydrolysates exhibited different levels of antimicrobial activity, with papain-derived hydrolysates being the most effective against *Staphylococcus aureus*, *Acinetobacter baumannii*, *Escherichia coli*, and *Salmonella* spp. The antioxidant properties of pigeon pea hydrolysates were evaluated using DPPH and FRAP assays. The tryptic hydrolysates showed the highest DPPH activity, while the FRAP assay indicated strong reducing antioxidant capacity. The study measured the peptide yield of pigeon pea protein hydrolysates. The yield percentage varied among different hydrolysates, with peptic hydrolysates showing distinct peptide recovery, which were 89.03 ± 3.10a; tryptic hydrolysates were 25.72 ± 1.79c; and papain hydrolysates were 75.38 ± 4.13b. Overall, the findings of this study of papain hydrolysates showed the widest spectrum of antibacterial activity, and hydrolysates obtained through trypsin digestion demonstrated the highest antioxidant activity. This study demonstrated that pigeon pea proteins can be enzymatically hydrolyzed to produce peptides with both antimicrobial and antioxidant properties. The choice of enzyme used for hydrolysis affects the bioactivity of the resulting peptides, with papain producing the best antimicrobial peptides and trypsin producing the best antioxidant peptides. They suggested potential applications for pigeon pea protein hydrolysates in food preservation, nutraceuticals, or pharmaceutical industries (Sharma et al. 2019).

4 | Antinutritional Constituents of Pulses and Their Mitigation Strategies

Despite these benefits as discussed in the above section, pulses naturally contain various ANCs also. Antinutritional compounds are divided into various groups, such as phytates, tannins, lectins, trypsin and chymotrypsin inhibitors, saponins, and certain oligosaccharides (Semwal et al. 2023) (Acquah et al. 2021; Bessada et al. 2019) (Table 3). These substances can bind to minerals, for example, iron, zinc, and calcium, reducing their bioavailability, or inhibit digestive enzymes, thereby lowering protein digestibility. Some compounds, like lectins, can cause gastrointestinal discomfort if consumed raw or undercooked. However, some compounds may have potential health-promoting effects in low concentrations, including

TABLE 3 | Antinutritional phytochemicals present in pulses, sources, and their effects.

Sr. No.	Phytochemicals	Part of pulses	Effects	References
1.	Phytic acid	Cotyledons	Metabolism ↓	(Acquah et al. 2021; Bessada et al. 2019)
2.	Lectins	Seed coat	Metabolism ↓ anticancer and immune-modulating activity	(P. Wang et al. 2021) (Acquah et al. 2021; Bessada et al. 2019)
3.	Tannins	Seed coat	Mineral absorption ↓	(Acquah et al. 2021; Bessada et al. 2019)
4.	Saponins	Cotyledons	Enzyme inhibition along with antimutagenic, anti-inflammatory, neuroprotective, and anticancer properties.	(López-Moreno et al. 2022)
5.	Oligosaccharides	Cotyledons	Mineral absorption ↓	(Acquah et al. 2021; Bessada et al. 2019) (López-Moreno et al. 2022)
6.	Goitrogen	Cotyledons	Inflammation ↑	(López-Moreno et al. 2022)
7.	Cyanogenic glycosides	Cotyledons	Inflammation ↑ and digestion ↓	(López-Moreno et al. 2022)
8.	Toxic amino acid	Cotyledons	Digestion ↓	(López-Moreno et al. 2022)
9.	Enzyme inhibitors	Cotyledons	Metabolism ↓	(Acquah et al. 2021; Bessada et al. 2019)

antioxidant, cholesterol-lowering, and glycaemic-modulating properties (Arnal et al. 2024; Mustafa et al. 2022). Thus, their role in nutrition is complex because they act as both inhibitors of various functions of human physiology and have some health benefits. Various techniques, such as soaking, sprouting (germination), fermentation, and proper heat treatment, can inactivate or greatly mitigate the ANCs. These processes or methods have been implemented by humans for centuries. Although these traditional techniques play a crucial role in reducing the adverse effects of these compounds, it is essential to first understand the major antinutritional factors present in pulses. The following section briefly discusses various types of ANCs and methods to reduce them.

4.1 | Tannins

Structurally, tannins are classified as water-soluble polyphenolic compounds present in pulses, cereals, fruits, and vegetables. They are widely found in different parts of plants such as seeds, seed coats, leaves, and other tissues. They are considered important antinutritional factors because they have a tendency to bind and precipitate dietary proteins and inhibit the absorption of essential minerals such as iron and zinc by forming insoluble complexes in the gastrointestinal tract.

Tannin levels in pulses vary greatly depending on species, genotype, and seed coat color. In beans, darker colored varieties generally show higher tannin content, ranging from 1.3 to 2.0 g per 100 g, whereas white beans have negligible amounts (~0.003 g/100 g). Red kidney beans demonstrate wide variability, with reports from as low as 210 mg/100 g to over 4500 mg/100 g. Pigeon peas display similar diversity, from as low as 61.5 mg/100 g in the 7D variety to over 3000 mg/100 g in high-tannin genotypes. Horse gram seeds consistently exhibit high tannin concentrations (0.76%–0.90% by weight), whereas mung beans range from ~477 mg/100 g in Pusa Baisakhi to over 768 mg/100 g in Ethiopian varieties. Lentils generally contain 0.44- to 1.94-g/100 g tannins, although certain genotypes can reach exceptionally high values. Rice bean tannins range from 1.00% to 1.44%, with condensed and hydrolysable fractions contributing distinct proportions. Cowpeas, like beans, concentrate tannins in their seed coat, with testa values reaching up to 11,600 mg/100 g, compared to as low as 30 mg/100 g in some varieties (Idris et al. 2025; Nagessa et al. 2023; Pokharel et al. 2024; Riaz et al. 2024; Rudra et al. 2023).

Processing techniques significantly lower tannin levels by disrupting the seed coat and altering phenolic structures. In horse gram, dehulling reduces tannin content from ~817 to 290 mg/100 g, whereas soaking and germination produce further reductions. Mung beans show notable decreases with common household treatments—roasting reduces tannins by ~21%, soaking by ~38%, germination by ~37%, and dehulling by ~63%. In cowpeas, decortication decreases tannins from ~760 to 2 mg/100 g, with roasting driving an additional minimal reduction. These findings highlight that both mechanical and biological processes effectively reduce tannin levels, with dehulling consistently showing the greatest impact. This has important implications for improving the nutritional quality of pulse-based diets, particularly in populations where high tannin intake may limit protein and mineral bioavailability (Idris et al. 2025; Nagessa et al. 2023; Pokharel et al. 2024; Riaz et al. 2024; Rudra et al. 2023).

4.2 | Phytates

The phytic acid is the key source of phosphorus (Angel et al. 2002). These compound salts are phytates, which help prevent several health issues and their effects, including anticarcinogens and reducing the chances of heart disease or diabetes. The compound is significant for seed constituents because of its presence in all nuts, including cereals, pulses, and oil seeds, at around 1%–3% (Nissar et al. 2017).

Phytate content in pulses shows substantial variation depending on species, genotype, and analytical method. Common beans contain between 507 and 2566 mg per 100-g DW, aligning with the general pulse range of 0.27%–2.90% of dry matter. Pigeon peas typically have 1.57–6.54 mg/g, equivalent to 0.16%–0.65%, with some reports averaging around 4.8 g/100 g. Horse gram shows a particularly wide range (1.07–21.2 mg/g), with average values near 1.02%, making it one of the higher phytate-containing pulses. Mung beans vary from ~626 mg/100 g in typical cultivars to over 2000 mg/100 g in certain genotypes. Lentils are generally lower in phytate, ranging from 250 to 1191 mg/100 g, whereas rice beans contain 205–432 mg/100 g depending on genotype. Cowpeas fall in the moderate-to-high category, with 660–1880 mg/100 g, although literature reports extend up to 3.0% in some cases. These differences reflect both genetic diversity and environmental influences on phytate accumulation (Affrifah et al. 2022; Boeck et al. 2021; Cominelli et al. 2022; Dwivedi et al. 2015; Narale et al. 2024; Padhi et al. 2022; Sekhon et al. 2017; Sinkovič et al. 2022).

Processing treatments can markedly reduce phytate levels by removing the seed coat or activating endogenous phytase enzymes. In lentils, dehulling reduces phytate by ~53%–56%, germination by 40%–59%, and cooking further lowers levels to 160–210 mg/100 g. Similar trends occur in other pulses; decortication in lentils and cowpeas eliminates a significant portion of phytic acid, as much of it is concentrated in the outer layers. Germination enhances phytate degradation through enzymatic hydrolysis, whereas thermal treatments such as boiling or steaming can improve solubility and facilitate leaching into cooking water. However, the efficiency of reduction depends on initial phytate levels, seed structure, and processing intensity. These findings highlight that the strategic application of traditional techniques to reduce antinutrients can significantly improve mineral bioavailability from pulse-based diets, making them nutritionally more beneficial (Affrifah et al. 2023; Boeck et al. 2021; Cominelli et al. 2022; Dwivedi et al. 2015; Narale et al. 2024; Padhi et al. 2022; Sekhon et al. 2017; Sinkovič et al. 2022).

4.3 | Trypsin Inhibitors

Trypsin inhibitor activity (TIA) in pulses shows substantial variability depending on species, genotype, and measurement approach. Pigeon pea seeds exhibit moderate activity, averaging ~4.75 U/mg, with high-yielding cultivars such as UPAS-120 and ICPL-87 ranging between 1007 and 1082 TIU/g. Horse gram, by contrast, displays notably high TIA, with values around 9.25 U/mg in raw flour and up to 12.18-mg TIA/100 g in some reports. Mung bean is among the lowest, typically ~1.83 U/mg, with Chinese cultivars showing even lower averages (~0.039 U/mg). Lentils fall in the intermediate range, with raw whole and split types averaging 5.0–6.3 TIU/mg. Rice bean genotypes show TIA between 1.13 and 1.64 U/mg, whereas cowpea demonstrates moderate-to-high activity (~8.0 TIU/mg in whole flour) with significant variation across cultivars (< 10 to 47 TIU/mg). These variations reflect not only species-specific protein inhibitor levels but also genetic diversity within cultivars. Processing methods significantly lower TIA by denaturing inhibitor proteins and facilitating their leaching from seeds. In pigeon pea, soaking followed by boiling reduces TIA by ~80%, whereas simple boiling or autoclaving lowers activity from ~5.6 to ~2.3 U/mg. In horse gram, converting dehulled flour into protein concentrate decreases TIA by ~48.5%, whereas fermentation reduces it by nearly 79%. Mung bean germination decreases TIA modestly (from ~1.8 to 1.2 U/g over 5 days). In lentils, dehulling, germination, and cooking all markedly reduce TIA, with combined soaking and cooking effectively eliminating detectable activity. Fermentation of lentil flour achieves reductions of ~62.5%. Rice bean and cowpea also respond well to thermal treatments, although processing effects vary with genotype. Overall, thermal and fermentation-based processing are the most effective strategies for minimizing trypsin inhibitors, thereby improving protein digestibility and nutritional value in pulse-based diets (Iqbal et al. 2006; Katoch 2013; K. Liu 2021; Mittal et al. 2012; Mubarak 2005; Sreerama et al. 2012).

4.4 | Lectins (Haemagglutinins)

Lectins are carbohydrate-binding proteins widely distributed in pulses, where they play important biological roles but can also exhibit antinutritional effects if consumed in high amounts without adequate processing. *Phaseolus vulgaris*, particularly red kidney beans, contains high levels of phytohemagglutinin, reaching up to 70,000 hemagglutinating units (HAU) per gram in raw form, which can be reduced to 200–400 HAU/g through proper cooking. Within this species, specific lectin types such as PHA-L, PHA-E, and PHA-M show distinct biochemical activities, ranging from mitogenic stimulation to red blood cell agglutination. Other pulses, such as *Cajanus cajan* (pigeon pea), *Macrotyloma uniflorum* (horse gram), and *Lens culinaris* (lentil), also contain lectins with varied sugar-binding specificities and structural properties, including mannose-specific dimers and metalloproteins. Importantly, cooking, especially pressure cooking, can reduce or completely inactivate lectins, mitigating their potential toxicity. Beyond these examples, rice bean lectin is specific for β-D-galactose, N-acetyl-D-glucosamine, and lactose, whereas cowpea lectins are non-specific and lack blood group specificity. Both species demonstrate measurable erythrocyte agglutination activity, suggesting potential roles in immune modulation and cell signalling studies. As with other pulses, processing methods like soaking, cooking, germination, and autoclaving substantially reduce lectin content, enhancing safety and digestibility (He et al. 2018; Kelkar et al. 2012).

4.5 | Saponins

Saponins are bioactive compounds with dual nutritional roles. Although excessive intake may act as an antinutrient by impairing lipid absorption or causing bitterness, moderate levels have

been linked to beneficial effects such as lowering cholesterol, regulating blood sugar, and exhibiting anticancer potential. Saponin concentration in edible pulses varies widely depending on species, genotype, and analytical approach. Common beans generally contain 100–200 mg per 100 g, with soyasaponins such as Af and αg being dominant. Pigeon pea shows much higher levels, from about 473 mg to over 2299 mg per 100 g, with significant variation between varieties, such as the low-saponin 7D type and the high-saponin NSWCC 34A. Horse gram seed coats are notably rich in saponins (~2.5% by weight), alongside other phytochemicals. Mung beans exhibit considerable variability, with average saponin levels around 0.74% of DW but certain varieties exceeding 2.6%. Lentils typically contain 170–350 mg per 100 g, although solvent extracts reveal much higher concentrations in ethanol-soluble fractions. Rice beans usually have low native saponin content (< 3.1 mg/100 g), but ethanol extraction can yield ~2.5% by weight, highlighting the role of extraction methods in quantification. Cowpea has some of the lowest reported levels (0.13–0.23 mg/100 g), making it comparatively low in saponins among the pulses studied (Bajaj 2014; Donat et al. 2014; Lee et al. 2011; Mohanraj 2021; Shang et al. 2016). The variation in saponin content across pulses suggests that certain species, such as pigeon pea, horse gram, and specific mung bean varieties, can be significant dietary sources, whereas others, like cowpea, contribute minimally. For the consumption of these pulses as a dietary source, methods like soaking and germination are used (Bajaj 2014; Donat et al. 2014; Lee et al. 2011; Mohanraj 2021; Shang et al. 2016).

4.6 | Oxalates

The other compound is oxalic acid, which is present in various plant categories. These compounds exist in the cell sap of the plant in the form of salts, like potassium and calcium (Franceschi and Nakata 2005). Pulses are also a source of minerals because of the presence of phytate acid and oxalic acid; their bioavailability is less critical than that of other foods (Sandberg 2002).

The oxalate content in pulses shows considerable variation across species, influencing their dietary suitability, especially for individuals prone to kidney stone formation. Among the species examined, *Vigna unguiculata* (cowpea) has the lowest oxalate content (0.09–0.32 mg/100 g), followed by *Vigna umbellata* (rice bean) with moderate levels (23.17–34.24 mg/100 g). In contrast, *Phaseolus vulgaris* (common bean) displays a wide and often high range (65–548 mg/100 g), posing a comparatively greater oxalate load. Similarly, *Lens culinaris* (lentil) exhibits low oxalate content (1.3–24.0 mg/100 g), whereas *Macrotyloma uniflorum* (horse gram) has intermediate levels (124 mg/100 g), and *Cajanus cajan* (pigeon pea) records significantly higher amounts (310.50 mg/100 g). These values underline the importance of species-specific selection when designing diets for oxalate-sensitive populations. Processing methods play a pivotal role in mitigating oxalate levels and enhancing the nutritional safety of pulses. For *Vigna umbellata*, *Phaseolus vulgaris*, and lentils, boiling and soaking are effective for the mitigation of oxalates, whereas another process, like autoclaving, is used to achieve substantial reductions in *Vigna unguiculata*. Malted seeds of *Cajanus cajan* showed drastically reduced levels of oxalates from 1.78 to 0.02 mg/100 g (Bajaj 2014; Q. T. Liu et al. 2002; Słupski et al. 2011).

4.7 | Alkaloids

Alkaloids are important bioactive compounds, and they are produced in plant cells through specialised biosynthetic pathways (Shikimate pathway–derived alkaloids, Ornithine and Arginine pathway, Lysine pathway, Aspartate pathway, or Polyketide–amino acid condensation pathways). The content of alkaloids in pulses varies from species to species, and the presence of these compounds influences their nutritional quality and potential health impacts. Like saponins, they also exhibit dual roles, offering beneficial bioactivities such as antimicrobial and therapeutic effects while also posing adverse impacts due to potential toxicity and interference with nutrient absorption. In the context of Indian-grown pulses, horse gram (238–312 mg/100 g) and rice bean (645 mg/100 g) have higher amounts of alkaloid levels, whereas cowpea (81 mg/100 g) and kidney beans (128–164 mg/100 g) have moderate levels of alkaloids. Low alkaloid-containing pulses like pigeon pea and lentil are reported at less than 20 mg/100 g. These differences highlight the importance of species-specific evaluation when considering the dietary alkaloid load, especially for sensitive groups (Jallow et al. 2013; Khokhar and Apenten 2003; Samtiya et al. 2020).

Various methods are involved in the reduction of alkaloid content to improve safety and make pulses easier to consume. In pigeon pea, fermentation and toasting can reduce alkaloid content to as low as 1.48 mg/100 g, whereas in lentils, soaking followed by cooking markedly lowers levels. Cowpea and common bean also benefit from prolonged soaking, discarding soak water, and adequate boiling, which effectively diminishes alkaloid concentrations. Although specific data on alkaloid reduction for horse gram and rice bean are limited, traditional culinary processes are likely to contribute to a meaningful decrease. Therefore, combining informed species selection with appropriate processing techniques is a key strategy to minimise alkaloid intake while retaining the nutritional value of pulses (Jallow et al. 2013; Khokhar and Apenten 2003; Samtiya et al. 2020).

4.8 | Techniques to Reduce Antinutrients in Pulses

As discussed in Section 3 above, different antinutrients present in pulses can hinder their nutritional value and digestibility. Different techniques can be used to reduce antinutrient levels and improve nutrient absorption in pulses. Both thermal and nonthermal methods can affect the phytochemical composition of pulses. For example, phenolic compounds, protease inhibitors, and lectins are antinutritional factors that are partly heat-resistant, and processes such as soaking, boiling, or fermentation can effectively reduce their levels. In contrast, other ANCs such as tannins, saponins, and phytic acid survive the heat and are more resistant to thermal processing. The primary methods like dehulling, soaking, roasting, fermentation, irradiation, air classification, and extrusion are well-defined for the techniques to reduce antinutrients methods, as shown in Figure 6 (Oyeyinka et al. 2022). On the other hand, some biological techniques, namely, enzyme treatments, germination, and fermentation, are more effective than primary technology. Different thermal and nonthermal processing techniques and their impact on the phytochemical composition of pulse seeds are explored in the next section (Zhou et al. 2024).

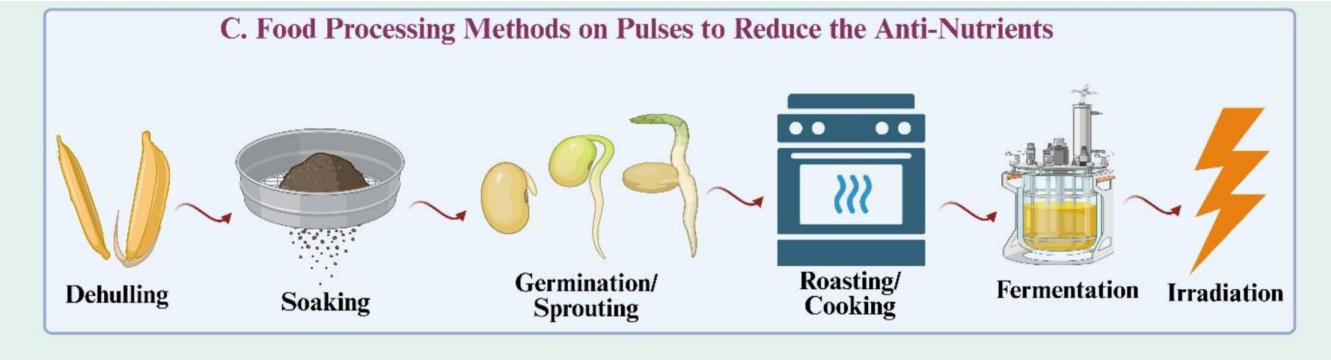


FIGURE 6 | Techniques to reduce antinutrients methods on pulses to reduce the antinutrients.

4.8.1 | Dehulling

The dehulling process improves the cooking qualities and enhances the nutritional values of pulses. To initiate the hulling process, the seed must undergo a pretreatment to help loosen the outer layers before removing the seed coats. A crucial step in dehulling is preconditioning, which reinforces the hull, reduces the adhesion between the cotyledons, and strengthens them to prevent breakage during processing. These methods can significantly lower their levels since polyphenols are mainly found in seed coats (Patterson et al. 2017).

It can be carried out via two techniques: wet or dry. In the wet method, the seeds are soaked in water or tempered before applying heat, whereas in the dry process, it is performed by using mechanical abrasion. In particular conditions, chemical solutions or heat treatments remove the hull. Although these methods are effective, they have certain limitations. For example, they may reduce the cooking quality or cause a change in the shape of the seed. Additionally, these processes are often labor-intensive and time-consuming. Also, it requires careful execution for the best results (Sreerama et al. 2009). For example, milling of black gram seed reduces the polyphenol content by approximately 25% present in the seed coat. This highlights the importance of retaining the seed coat to maximise the health benefits of these bioactive compounds (Devi et al. 2014).

4.8.2 | Soaking

The soaking method is used to reduce enzyme inhibitors in pulses. The purpose of this method is to minimise enzyme inhibitors like α-amylase inhibitors, trypsin inhibitors, and chymotrypsin inhibitors in pulses (Shi et al. 2017). Soaking in pulses is wholly submerged in water at room temperature, and the time range of soaking is from 3 to 48 h (Goss et al. 2014). The benefits of soaking are that it reduces cooking time and decreases certain ANCs in pulses. The water-soluble ANCs are extracted in water, or degrading enzymes are activated during soaking. Soaking time and soaking solution (water, salt solution, or bicarbonate solution) are key factors affecting the reduction of ANCs. At the end of the procedure, water will be discarded after the process to remove leached ANCs. An additional benefit of variations in soaking solution (using $NaHCO_3$ and Na_2CO_3 salt) is that it can reduce cooking time. Soaking showed a reduction in phytate levels due to the activation of phytase enzymes; at temperatures between 45°C and 60°C and pH levels of 5–6, the decrease in phytate levels is higher. It reduces tannin and polyphenol content through diffusion into water and can even reduce cyanogenic glycosides more effectively when using a sodium bicarbonate solution. It also decreases enzyme inhibitors like trypsin, α-amylase, and chymotrypsin by leaching them into the soaking water, although the effectiveness can vary depending on soaking conditions and seed structure. After washing, seeds may split, leading to more significant inhibitor reductions than whole seeds. Soaking can also reduce oligosaccharides through autolysis and extraction (Y. Kumar et al. 2022).

4.8.3 | Germination

Germination is when a dry seed absorbs water and ends when the seed's embryonic axis elongates. After the seed dormancy period, the protective mechanisms get activated, producing phenolics and other compounds. During this process, bean sprouts undergo nutrient changes. This process may increase seeds' nutrient content and reduce harmful substances like enzyme inhibitors. This marks the initial phase of plant growth, during which the primary root and stem emerge, and the seed's stored nutrients are used to support the development. The enzymatic system of the seed is also activated during germination, which is one of the most effective ways to improve the nutritional value of pulses and make nutrients because proteins and carbohydrates are broken down to provide necessary nutrients for seed development. This process makes protein and carbohydrates more digestible (Bewley et al. 1994). Various studies show that proteases play a significant role in deactivating protein-based ANCs like enzyme inhibitors and lectins. Studies also showed the conversion of phytic acid into inorganic phosphorus by the enzyme phytase, which is needed for plant growth. Germination also alters the phenolic content in pulses, quantitatively and qualitatively, and has been found to reduce the cyanide content in kidney beans by up to 20.8%. The additional advantage of germination is that it reduces the concentration of enzyme inhibitors like trypsin, α-amylase, and chymotrypsin in pulses (López-Martínez et al. 2017).

4.8.4 | Roasting

Roasting techniques to reduce antinutrients are another cooking method (Stone et al. 2021). Roasting provides suitable

conditions for a chemical reaction between amino acids and reducing sugars. It is also called the Maillard reaction, creating complex flavors and aromas. It is responsible for the characteristic smell of roasted coffee, toasted bread, and seared meats. In caramelization, sugars are heated to high temperatures during roasting, breaking down and forming new compounds, producing sweet and nutty aromas. During roasting, the melting and rendering of fat release volatile compounds that enhance the overall aroma. The concentration of roasting flavors often involves dry heat, which can concentrate flavors by evaporating moisture. The all-around heat exposure in roasting can lead to more uniform flavor development than other cooking methods. It is essential to cook pulses before consumption to enhance taste, texture, digestibility, and availability of nutrients. In the roasting process, antioxidant activity reduces antinutrient activity and microbial loads. Various cooking methods can be used in roasting, such as grilling, boiling, roasting, and steaming. The type of cooking depends on the food material and its thermosensitivity. The old processing of pulses is generally completed in two stages. In the first stage, the whole seeds are dehulled, reducing the antinutrients, and the second stage is followed by soaking, autoclaving, germination, roasting, and fermentation. The types of roasting included sand roasting, microwave roasting, micronization/infrared roasting, and continuous spiral roasting (Meda et al. 2018).

4.8.5 | Fermentation

Fermentation is a vital processing technology for food, improving the sensory qualities of food safety (by reducing infective microorganisms) and providing helpful health benefits (Behera et al. 2018). This method has multiple advantages in the case of pulses, including enhancement of quality, color, flavor, and storage time, along with improved digestion of protein. The fermented pulse has a higher probiotic active substance like oligosaccharides (FOS and RFOs), sugar alcohols, and resistant starch that improve insulin sensitivity. These fermented products also help in metabolism, particularly in men. This molecule also helps reduce pathogenic bacteria in the stomach and gastrointestinal tract while promoting the growth of beneficial microorganisms such as Lactobacilli and Bifidobacteria. Additionally, fermentation of cowpea and black bean produces SCFAs, which support better intestinal health. Another benefit of fermentation is an increase in bioactive peptides that contribute to therapeutic activity, such as antihypertensive, antioxidant, and ACE inhibitory effects (Byanju et al. 2021).

5 | Conclusion and Future Perspective

Pulses are a major group of foods, providing protein, dietary fibers, and several secondary metabolites with significant health benefits. These plants belong to the pulse family, and most are consumable, including chickpeas, kidney beans, pigeon pea, horse gram, beans, and lentils. They are a high source of fiber, protein, vitamins, and minerals (especially B vitamins, iron, zinc, magnesium, and potassium) and are low in fat. They contain multipurpose ingredients that can be incorporated into the human diet. They are also environmentally sustainable crops. This review concluded that the phytochemical properties of pulses included antioxidant, anti-inflammatory, anticancerous, antimicrobial, and various other beneficial properties. The nutritional benefits of pulses are high in protein and fiber, and the focused health implications of the consumption of pulses may help reduce the risk of various diseases. The primary health organizations, including the FAO, recommend pulses to decrease the risk of chronic diseases.

In the current application, despite their health benefits, pulse consumption is relatively low. The main reason suggested for low consumption is the lack of easily accessible information about pulses in this literature, and in this review, we focused mainly on four types of pulses, including chickpeas, kidney beans, horse gram, and pigeon peas, which are mostly grown in India. This review provides a piece of information on different types of pulses and their chemical constituents. This information could increase awareness and utilization of pulses, and future research may focus on discovering new active components of pulses.

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Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

Data sharing is not applicable to this article as no datasets were generated or analyzed during the current study.

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