Received: 27 August 2024 | Revised: 6 February 2025 | Accepted: 12 February 2025

DOI: 10.1111/1541-4337.70152

COMPREHENSIVE REVIEW

Comprehensive review of chickpea (*Cicer arietinum*): Nutritional significance, health benefits, techno-functionalities, and food applications

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Funding information
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Abstract

Chickpeas (*Cicer arietinum* L.) are globally valued legume known for their affordability, nutritional significance, and health benefits. They are rich in protein, fiber, vitamins, and minerals such as iron, zinc, folate, and magnesium. This review comprehensively explores the chemical composition of chickpeas and their functional properties, focusing on macronutrients, micronutrients, phytochemicals, and antinutritional factors. It also delves into the potential health benefits of bioactive compounds and peptides derived from chickpeas, highlighting their roles in various physiological functions and applications. The exceptional technofunctional properties of chickpea proteins, including gel formation, texture enhancement, emulsification, and fat/water binding, make them ideal ingredients for diverse food products. Their versatility allows for use in various forms (isolates, concentrates, textured proteins), contributing to the development of a wide range of plant-based foods, nutritional supplements, and gluten-free options. While chickpeas contain some antinutrients like phytates, lectins, and enzyme inhibitors, effective processing methods can significantly reduce their potential negative effects. This review provides valuable insights, offering the novel contributions and an enhanced understanding it brings to the scientific community and food industry. By bridging compositional data with physiological implications, the review reinforces the pivotal role of chickpeas as a dietary component and enriches the existing scientific literature on this essential legume.

KEYWORDS
chickpea, health benefits, nutritional composition, proteins, technofunctional properties

1 | INTRODUCTION

Chickpeas (*Cicer arietinum* L.), a vital legume belonging to the tribe Cicereae, subfamily Faboideae (or Papilionoideae), and family Fabaceae (or Leguminosae), are a rich source of protein, fiber, vitamins, and minerals, making them a significant component of global diets (Sandhu et al., 2023). There are two primary types of chickpeas, based on plant type, pigmentation, flower, and seed size (Toker et al., 2014): kabuli, characterized by its larger seeds ranging from 0.2 to 0.6 g, smooth texture, and light tan color, and the Desi type, with its small, angular seeds

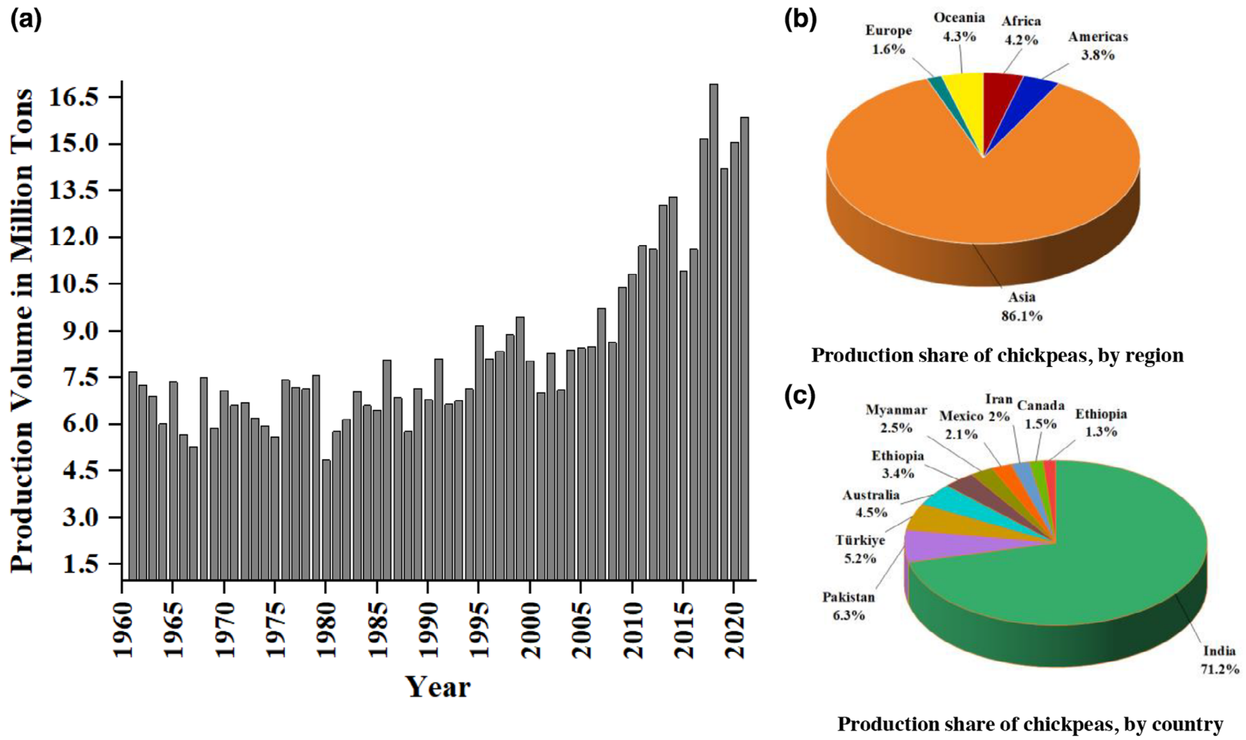

FIGURE 1 Global chickpea production from 1961 to 2021, showcased by (a) global output, (b) regional distribution, and (c) country-specific data. *Source*: FAO database in November, 2023.

ranging from 0.1 to 0.3 g, dark brown color, and crusty skin. Desi chickpeas, often used whole, split, or ground into dhal or flour, are popular in dry pulse dishes and sauces like hummus or soups. In contrast, Kabuli varieties are commonly used in salads and vegetable mixes and are often found canned or as flour (Swamy, 2023).

Chickpeas likely originated in the region of South-East Anatolia, alongside parts of Syria and Iran. The earliest remnants suggest the legume dates back to around 7000 BC. From there, chickpeas spread to the Mediterranean Basin, Africa, and the Indian subcontinent before 2000 BC (Swamy, 2023). The name *Cicer* is of Latin origin and may be derived from the pre-Indogerman *kickere* in the Pelasgian language of the tribes populating northern Greece before Greek-speaking tribes took over. The oldest reference to the Latin epithet *arietinum* was found in Columella's work, probably as a translation (Van der Maesen, 1987). The genus *Cicer* has been reportedly contains up to 45 different taxa, including nine annuals and 36 perennials (Toker et al., 2014). Interestingly, *C. arietinum* L. is the only cultivated species in the genus (Toker et al., 2014). For a detailed review of the history and taxonomy of chickpea, the reader is referred to the work of Van der Maesen (1987), updated by Toker et al. (2014).

Chickpeas are now grown in over 50 countries worldwide, and global production has significantly increased in the 21st century, reaching around 17 million tons in 2021 (FAO, 2023a), as shown in Figure 1. India is the world's leading producer of chickpeas, accounting for about 71.2% of global production. Other major chickpea-producing countries include Pakistan with 6.3%, Turkey with 5.2%, Australia with 4.5%, Ethiopia with 3.4%, Myanmar with 2.5%, and Iran with 2.0%. Canada and the United States are relatively minor producers, accounting for only 1.3%–1.5% of global production (FAO, 2023a).

Despite the long history of chickpea consumption as a nutritious food source, there has been a resurgence of interest in chickpeas over the past two to three decades. Many research studies highlight the potential health benefits of chickpeas and explore their use in food applications. Global consumption of chickpeas varies according to regional and cultural preferences (Jukanti et al., 2012). In the Indian subcontinent, they are often split into "dhal" or ground into "besan" flour for the preparation of traditional snacks (Chavan et al., 1987). Other parts of the world, particularly Asia and Africa, incorporate chickpeas into stews, soups, and salads and consume them in various forms, such as roasted, boiled, salted, or even fermented (Jukanti et al., 2012). This diversity offers consumers a range of nutritional and potential health benefits. Malnutrition, characterized by deficiencies in proteins, calories, minerals, and vitamins, is a serious and growing problem in developing countries. Data from the Food and Agriculture Organization indicate that nearly between 691 million and

783 million people globally were undernourished in 2022 (FAO, 2023b). In regions where animal proteins are less accessible, incorporating plant-based protein sources like pulses can help meet protein needs and potentially contribute to managing malnutrition and kwashiorkor (a form of malnutrition caused by protein deficiency) in children (Gao et al., 2023; Sandhu et al., 2023).

Studies comparing chickpeas to other legumes like peas and lentils examine protein composition, functionality, texture, and application in extruded meat alternatives. These investigations emphasize the nutritional significance of chickpeas and demonstrate their potential for developing healthy and sustainable food products (Nkurikiye, Chen, et al., 2023; Nkurikiye, Pulivarthi, et al., 2023; Wang et al., 2022, 2023). Chickpea flour, also known as gram flour or besan (in the case of decorticated, milled Desi chickpea), is a versatile and nutritious ingredient that has been used in various cuisines for centuries. Derived from ground chickpeas, this pale golden powder offers a host of benefits. It is gluten free, making it an excellent choice for those with gluten intolerance. Notably, it has fewer calories than traditional refined wheat flour and is known to promote satiety (Rachwa-Rosiak et al., 2015). Chickpea proteins are highly bioavailable and provide essential amino acids, making them an excellent source of dietary protein. Chickpea proteins also exhibit excellent functional properties, making them suitable for developing protein-enriched ingredients (Grasso et al., 2022; Jukanti et al., 2012). They are gaining consumer acceptance as a functional food due to their exceptional nutritional profile. Recent research suggests potential health benefits associated with chickpea consumption, including beneficial effects on various chronic diseases like cardiovascular disease, type 2 diabetes, digestive issues, and certain types of cancer (Fernando et al., 2010; Jukanti et al., 2012; Kaur & Prasad, 2021; Kerem et al., 2007). Furthermore, a study by Nkurikiye et al. (2023) demonstrated that incorporating chickpea flour can enhance mixing tolerance and dough strength of wheat flour, suggesting additional functional applications of chickpeas in food processing and potential benefits for metabolic health (Nkurikiye, Chen, et al., 2023).

Beyond their nutritional value and health benefits, chickpeas are indeed an important crop for sustainable agriculture through their nitrogen-fixing capabilities. This can help to reduce the need for chemical fertilizers and improve soil fertility (Agarwal, 2023). The nitrogen-fixing capability of chickpeas stems from their symbiotic relationship with nitrogen-fixing bacteria, enabling them to obtain up to 70% of their nitrogen requirements through this process (Kahraman & Buğdaylı, 2023). This symbiotic relationship not only benefits the chickpea crop itself but also enhances soil fertility, as chickpeas can fix nitrogen at rates reaching 140 kg/ha/year (Swamy, 2023).

While past studies have explored the nutritional profile and health benefits of chickpeas, a comprehensive understanding that integrates their composition, functional properties, emerging bioactive compounds, and recent advancements is essential. Previous reviews and publications on chickpeas, such as those by Bampidis and Christodoulou (2011), Chavan et al. (1987), Jukanti et al. (2012), Kaur and Prasad (2021), Mathew et al. (2022), Rachwa-Rosiak et al. (2015), and Yegrem (2021), provide valuable insights. However, our review uniquely integrates compositional and nutritional data with cellular and histological analyses, offering a deeper understanding of how chickpeas deliver their nutritional benefits. This approach addresses existing gaps in the literature and provides novel insights into the potential of chickpeas as a key component of a healthy diet. This review aims to comprehensively explore the multifaceted world of chickpeas, delving deep into their nutritional significance and potential health benefits. We begin by highlighting the kernel properties of chickpeas, followed by an in-depth analysis of macronutrients (carbohydrates, proteins, and fats) and micronutrients (minerals, vitamins, and phytochemicals). We then explored the functional properties of chickpea proteins, focusing on their unique characteristics like solubility, water-holding capacity (WHC), and emulsifying abilities. The chemical and functional properties of chickpea starch have also been explored, emphasizing its potential applications in food systems. We have then explored the applications of chickpeas, ranging from their use in traditional dishes to their emerging roles as protein ingredients, aquafaba, and bioactive peptides with promising health benefits and others. Finally, we have discussed the future perspectives and provided insightful conclusions.

We conducted our literature review using reliable academic databases, including PubMed, Web of Science, and Google Scholar. We used Boolean operators while employing the keywords, which included "chickpea," "chickpea AND kernel property," "chickpea AND nutritional composition," "chickpea AND chemical composition," "chickpea AND amino acid composition," "chickpea AND proteins," "chickpea AND anti-nutritional factors," "chickpea AND functional properties," "chickpea AND starch," "chickpea AND food applications," "chickpea AND bioactive peptides," and "chickpea AND health benefits." The majority of references used in this review are from 2000 to 2024, with a significant proportion of studies published in recent years to ensure that recent advancements are adequately covered. Additionally, a few older, seminal studies have been included to provide historical context and foundational knowledge where necessary.

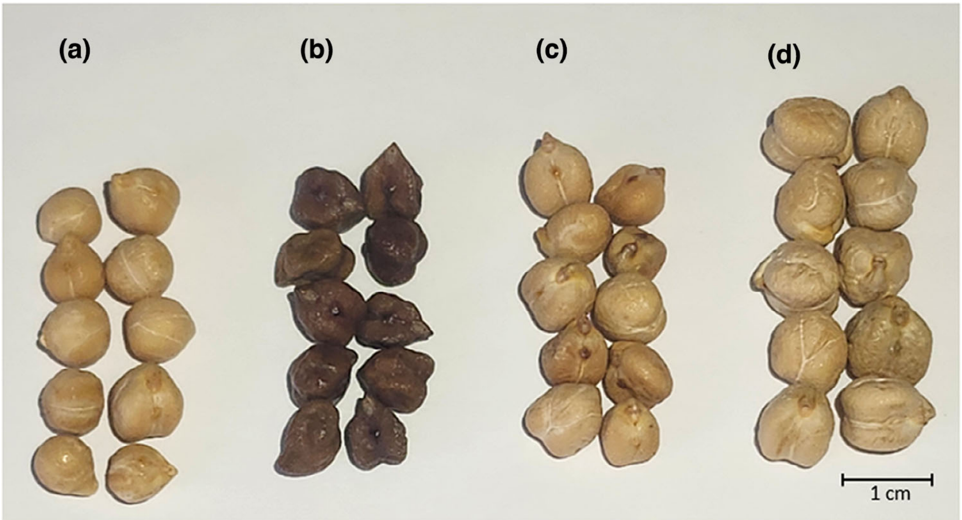

FIGURE 2 Chickpea varieties commercially available in the United States: (a) Marvel (Kabuli); (b) Desi; (c) Billy Bean (Kabuli); and (d) Orion (Kabuli).

TABLE 1 Kernel properties of chickpea seeds.

	Sastry et al., 2019		Ravi & Harte, 2009		Tripathi et al., 2012		Gnyandev et al., 2019	
	Desi mean	Kabuli mean	Desi	Kabuli	Desi	Kabui	Desi	Kabuli
Length (mm)	7.5	8.4	5.28–8.5	7.52–10.4	–	–	7.0–11.5	7.5–11.0
Width (mm)	5.4	6.6	5.6–7.4	7.25–8.33	–	–	–	–
Thickness (mm)	5.3	6.8	–	–	–	–	–	–
100-seed weight (g)	13.2	24.1	18.36–22.01	37.70–42.03	10.5–26.5	13.5–58.6	20.73–39.02	25.52–38.32
Geometric mean diameter (mm)	6.0	7.2	–	–	–	–	–	–
Sphericity (%)	79.5	85.7	–	–	–	–	–	–
Roundness	–	–	–	–	–	–	–	–
Bulk density (g/mL)	0.702	0.691	0.744–0.772	0.757–0.780	–	–	–	–
True density (g/mL)	1.293	1.261	1.26–1.33	1.226–1.260	–	–	–	–

2 | KERNEL PROPERTIES OF CHICKPEA

The physical properties of chickpea kernels vary significantly among different accessions and germplasm types, including Desi, Kabuli, and intermediate types (Sastry et al., 2019) (see Figure 2). Kernel properties of chickpea include length, width, thickness, geometric mean diameter (GMD), sphericity, bulk density, true density, roundness, and weight (Table 1). Kabuli chickpeas generally have larger seed dimensions, including length, width, and thickness, compared to Desi varieties. They also have a noticeably higher seed weight, indicating their larger overall size and mass (Ravi & Harte, 2009; Sastry et al., 2019; Tripathi et al., 2012). In terms of shape, Kabuli seeds exhibit greater sphericity, making them more rounded than Desi seeds (Ravi & Harte, 2009; Sastry et al., 2019). The sphericity of chickpea seeds is a key physical property that significantly impacts their handling, processing, and quality assessment. Defined as the ratio of the surface area of a sphere with the same volume as the seed to the actual surface area of the seed, sphericity varies among chickpea varieties and is influenced by moisture content. On average, chickpea seeds exhibit sphericity values ranging from 79.55% to 80.77% (Laxmikanth et al., 2020). This property correlates with the GMD of the seeds, which ranges from 6.57 to 7.58 mm. Certain cultivars, such as the ILC variety, demonstrate higher sphericity compared to others. Higher sphericity values are often linked to superior seed quality and hydration properties, essential for cooking and processing, making them valuable traits for breeding programs (Sastry et al., 2019; Sivakumar et al.,

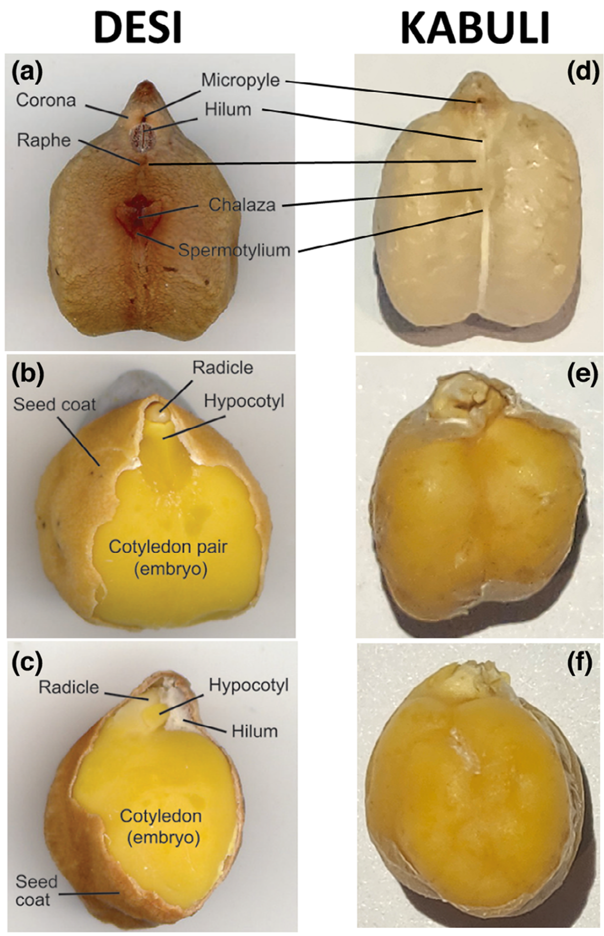

FIGURE 3 Chickpea (*Cicer arietinum* L.) seed anatomy shown for Desi and Kabuli types. (a) Desi's ventral view showcasing key external features. (b) Desi's ventral view with the seed coat removed, revealing major internal structures. (c) Desi's lateral view with the seed coat removed, highlighting prominent internal features (adapted from Wood, Knights, et al. [2011]). (d) Kabuli's ventral view. (e) Kabuli's ventral view with the seed coat removed. (F) Kabuli's lateral view with the seed coat removed.

2023). Additionally, bulk density plays an important role in assessing seed quality. While the bulk density of Kabuli seeds is slightly lower than that of Desi varieties, their true density is comparable (Sastry et al., 2019). A previous study reported bulk densities of 0.763 g/mL for Desi and 0.769 g/mL for Kabuli chickpeas, with Desi types exhibiting a slightly higher true density (1.290 g/mL) compared to Kabuli types (1.246 g/mL) (Ravi & Harte, 2009).

Roundness, an indicator of seed shape, distinguishes Desi and Kabuli chickpeas in terms of their morphology and functional traits. Desi chickpeas are smaller (0.1–0.3 g), angular, and irregular with a pronounced beak, while Kabuli chickpeas are larger (0.2–0.6 g), rounder, and smoother with a subtler beak (Wood, Knights, et al., 2011) (see Figure 3). These morphological differences influence cooking behavior, with Desi types retaining their shape better and Kabuli types being more prone to splitting. Roundness also plays a vital role in genetic selection and milling performance, as rounded seeds yield higher milling rates (7% more dhal) due to thinner seed coats and enhanced water absorption (Knights et al., 2011; Wood et al., 2012). The trait exhibits high heritability and low genotype–environment interaction, underscoring its stability and importance in breeding programs aimed at improving chickpea quality and industrial profitability (Hossain et al., 2010).

The seed coat, the protective layer encasing chickpeas, tells a compelling tale of two textures (see Figure 4). Desi chickpeas have a thicker, tougher coat, constituting between 12% and 16% of their weight. Kabuli chickpeas, on the other hand, have a thinner and more delicate coat, weighing between 2% and 6% of their total mass (Sastry et al., 2019; Wood et al., 2014; Wood, Knights, et al., 2011). The smaller proportion of seed coat in Kabuli chickpeas has a significant impact on the whole seed composition, as the chemical composition of seed coat and cotyledons varies greatly. Seed coats are primarily cellulosic, whereas cotyledons are an energy reserve for seed germination and growth (Wood et al., 2014).

From a histological perspective, the chickpea seed coat contains two distinct regions, an external palisade (comprising, from outermost to innermost, the following layers: the outer cuticle, the outer palisade, and the inner palisade) and an internal parenchymatous region (comprising, from outermost to innermost, the following layers: the hypodermis-rich in hourglass cells-a distinct layer of parenchyma cells, and the inner cuticle). Interestingly, the hypodermis is typically thicker in Kabuli and thinner in Desi chickpea. Most varieties of Desi chickpea have an interspace region (150- to 250-μm thick) between the inner cuticle and the cotyledon devoid of cellular structures. For further details on seed coat architecture, including region thicknesses, cell description, and clear microscopy brightfield and fluorescence pictures, the reader is referred to Wood, Knights, et al. (2011).

Desi chickpeas often require dehulling, while Kabuli chickpeas can be enjoyed whole or minimally processed (Grasso et al., 2022; Yegrem, 2021). The difference in seed coat thickness as well as the level of adhesion between the seed coat and the cotyledon surface translates to contrasting processing needs. Challenges in chickpea dehulling and milling have been thoroughly studied (Wood & Malcolmson, 2021; Wood et al., 2014; Wood, Choct, et al., 2011). The milling quality of chickpea can be influenced by seed morphology, ultrastructure, and chemistry. Factors such as higher mineral content (especially calcium, which is richly localized in the seed coat) and protein content in the seed coat seem to correlate with higher difficulty for milling as well as higher difficulty to decorticate the seeds.

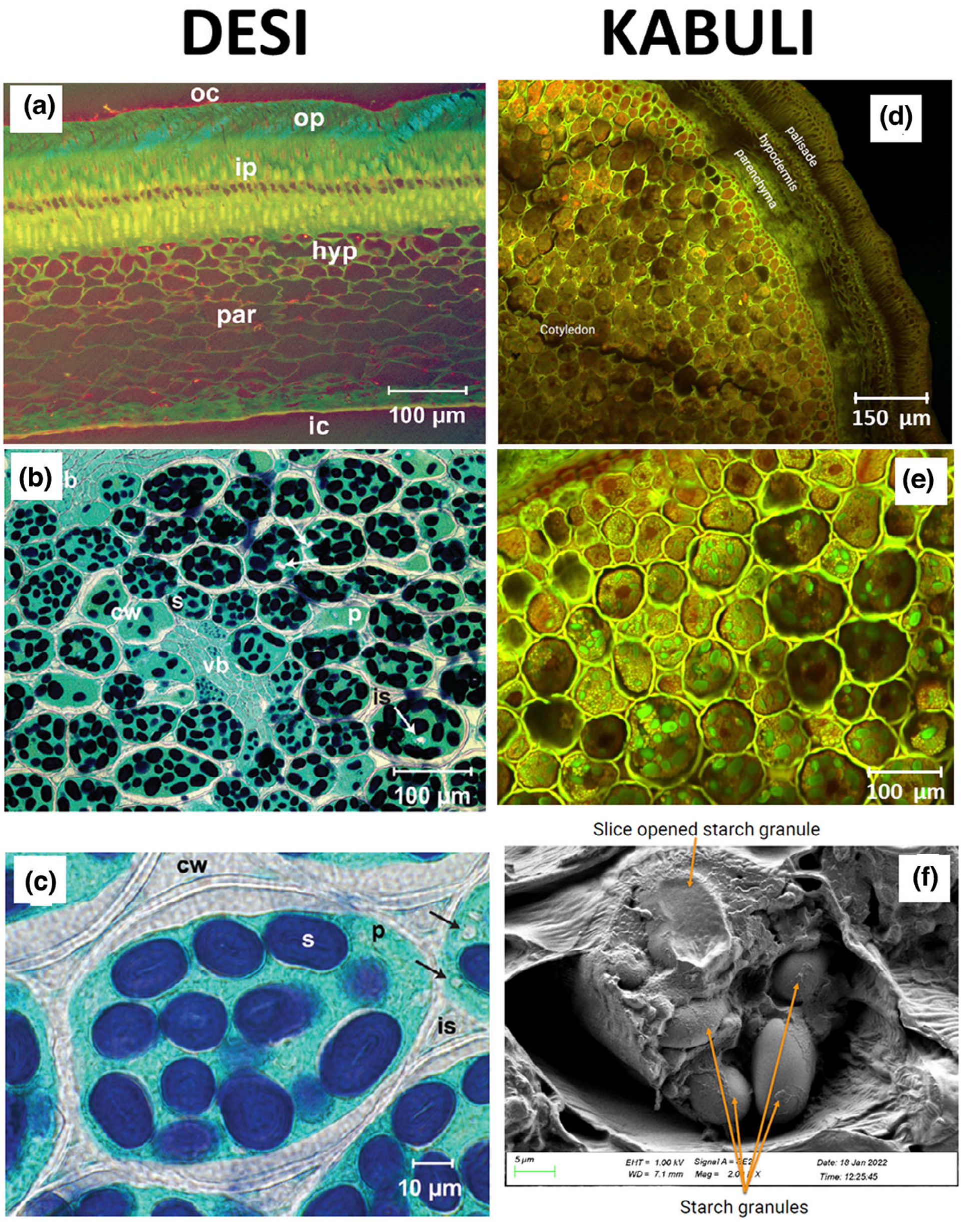

FIGURE 4 Microscopy pictures describing the seed coat and cotyledon microstructures. (a) Desi seed coat cross section, showing cellular structure, using fluorescence microscopy with acid fuchsin and calcofluor/fluorescent brightener to differentiate proteins and *β*-glucans, respectively. The image highlights key structural components, including the outer cuticle (oc), outer palisade (op), inner palisade (ip), hypodermis (hyp), parenchyma (par), and inner cotyledon (ic). Scale bar: 100 µm (Wood, Knights, et al., 2011). (b) Cross section of Desi chickpea inner cotyledon region, showing the cellular detail of vascular bundles. Vb, vascular bundle; s, starch granule; p, protein; is, intercellular space; cw, cell wall. Picture taken using bright-field mode and light green and Lugol's iodine solutions to highlight protein (in green) and starch granules (in blue), respectively (Wood, Knights, et al., 2011). (c) Detailed view of inner cotyledon cell of Desi chickpea. Same abbreviations apply as in (b) (Wood, Knights, et al., 2011). (d) Kabuli seed coat cross section, showing cellular structure and seed coat layers, using confocal microscopy. (e) Cross-section of Kabuli chickpea cotyledon, using confocal microscopy. (f) Detailed view of inner cotyledon cell of Kabuli chickpea using scanning electron microscopy. Pictures in panels (a)–(c) were published previously by Wood, Knights, et al. (2011). Panels (d)–(f) are unpublished material created internally at PepsiCo.

Beneath the seed coat lies the cotyledon, the heart of the chickpea kernel. Both Desi and Kabuli varieties have a similar internal structure, with two cotyledons composed mainly of parenchyma-type cells, packed with starch granules, protein bodies, and other essential nutrients. However, the cellular composition of these layers differs slightly (Sedláková et al., 2023; Wood, Knights, et al., 2011). Cells in Desi cotyledons exhibit thicker cell walls, contributing to their firmer texture. Cells in Kabuli cotyledons, on the other hand, have thinner cell walls, leading

TABLE 2 Nutrient composition (per 100 g) of chickpea seeds.

Nutrients	Khan et al., 1995 Desi and Kabuli	Candela et al., 1997	Alajaji & El-Adawy, 2006	Wallace et al., 2016	Yegrem, 2021 Desi and Kabuli	Koul et al., 2022	Mathew et al., 2022
Calories (Cal)	327–365	–	–	378	322–388	378–396	–
Protein (g)	24.4–25.4	19.15	23.64	20.47	14.01–24.91	18.8–24.0	18.7–23.6
Fat (g)	3.7–5.1	5.75	6.48	6.04	4.48–7.41	4.1–6.0	3.7–6.5
Carbohydrate (g)	47.4–55.8	50.54	62.34	62.95	52.61–67.66	39.7–54.2	39.6–62.6
Fiber (g)	3.9–11.2	–	3.82	12.2	4.23–16.91	7.4–12.2	3.8–25.2
Ash (g)	2.8–3.2	4.26	3.72	–	2.47–3.87	3.4	2.7–3.7

to a softer, more mealy texture. This difference in cell wall thickness influences culinary applications, with Desi chickpeas often being favored for their ability to retain their shape in dishes like curries, while Kabuli chickpeas are preferred for their smooth, creamy texture in hummus and falafel (Wood, Knights, et al., 2011). The outer periphery of chickpea cotyledons generally contains higher levels of protein, minerals, nonstarch polysaccharides, free sugars, and uronic acid but lower level of starch and lipid than the cotyledon core (Otto et al., 1997; Wood et al., 2014). Furthermore, cells in the outer periphery tend to be smaller and have a higher protein content (Wood et al., 2014).

The chemical composition of Desi and Kabuli chickpeas also diverges, influencing their nutritional profiles and culinary behaviors. Desi chickpeas boast higher levels of protein and fiber, making them a more satiating and nutrient-dense option. Kabuli chickpeas, in contrast, are richer in starch and have a lower glycemic index (GI), making them a suitable choice for those managing blood sugar levels (Soto-Madrid et al., 2023; Wood, Knights, et al., 2011; Xiao et al., 2023). These differences in kernel morphology and composition explain why Desi and Kabuli chickpeas are suited for various culinary applications.

3 | CHEMICAL COMPOSITION OF CHICKPEAS

Chickpeas are known for their rich nutritional profile, which varies depending on factors like genotype, climate, soil composition, and various forms of biological (biotic) or environmental (abiotic) stress (Chehade et al., 2024; Mohsenzadeh, 2024; Sari et al., 2024). This profile has made them a staple food since ancient times. Furthermore, chickpeas are gaining interest as a functional food with potential health benefits (Faridy et al., 2020). As shown in Table 2, chickpea seeds are a powerhouse of nutrients, packing an average of 18.7–24 g of protein per serving (100 g) for building and repairing tissues. They are relatively low in fat (4.1–6 g), making them a heart-friendly choice. Additionally, they are a champion of fiber (7.4–12.2 g), promoting gut health and digestion. Finally, chickpeas are a good source of carbohydrates (39.7–54.2 g) for sustained energy throughout the day (Koul et al., 2022). Hence, chickpeas are a versatile and nutrient-rich food that can be incorporated into various dishes to support a healthy diet. They are a rich source of carbohydrates, essential amino acids, protein, dietary fiber, calcium, iron, and phosphorus (Bampidis & Christodoulou, 2011). These nutrients can be divided into micronutrients, which the body needs in small amounts, and macronutrients, which are needed in larger quantities.

3.1 | Macronutrients in chickpea

3.1.1 | Carbohydrates

Chickpeas contain various carbohydrates, including polysaccharides (starch, fibers), oligosaccharides (stachyose, ciceritol, raffinose, and verbascose), disaccharides (sucrose and maltose), and monosaccharides (ribose, glucose, galactose, and fructose), as shown in Table 3 (Gupta et al., 2019; Jukanti et al., 2012). These carbohydrates can be divided into two categories based on how they are digested in the small intestine. The first group, available carbohydrates, includes monosaccharides, disaccharides, and digestible starch. The most abundant monosaccharides in chickpeas are galactose, ribose, fructose, and glucose. Maltose and sucrose are the most abundant disaccharides in chickpeas. The starches are broken down by enzymes during digestion and absorbed into the bloodstream. The second group, unavailable carbohydrates, includes oligosaccharides, resistant starch, non-cellulosic polysaccharides, pectin, hemicelluloses, and cellulose (Begum et al., 2023; Jayalakshmi et al., 2024). These complex carbohydrates cannot be digested by small intestine enzymes and pass through the digestive system

TABLE 3 Carbohydrate content in chickpea seeds (g/100 g).

Components	Chavan et al., 1987	Alajaji & El-Adawy, 2006	Aguilera, Martín-Cabrejas, et al., 2009	Mathew et al., 2022
Monosaccharides				
Ribose	–	–	–	0–0.05
Fructose	–	–	0.31	0.002–0.5
Glucose	–	–	0.05	0.03–0.30
Galactose	–	–	0.01	0.0–0.3
Disaccharides				
Sucrose	0.7–2.9	1.89	1.52	0.7–2.9
Maltose		–	0.33	0.0–0.2
Oligosaccharides				
Raffinose	0.5–3.0	1.45	0.32	0.2–1.4
Ciceritol		–	2.76	0.0–2.6
Stachyose	1.1–3.4	2.56	1.77	0.6–2.6
Verbascose	0.1–4.5	0.19	–	0.1–3.8
Melibiose		–	–	0.0–0.04
Polysaccharides				
Starch	37.2–50.8	36.91	33.73	35.7–54.9
Cellulose	7.1–9.7	–	–	3.0–4.0
Hemicellulose	3.5–8.7	–	–	2.7–7.8
Lignin	2.2–5.9	–	–	1.9–2.2
Pectin	1.5–3.8	–	–	0.0–4.2

intact (Jukanti et al., 2012; Wrigley et al., 2004). In the human digestive system, oligosaccharides like stachyose and ciceritol, which are not broken down or absorbed, are fermented by gut bacteria. This process can produce gases, potentially contributing to flatulence (Kadlec et al., 2000; Rachwa-Rosiak et al., 2015). Interestingly, α-galactosides, a prevalent type of carbohydrate in plants after sucrose, encompass two key groups in chickpeas: the raffinose family of oligosaccharides and galactosyl cyclitols. Ciceritol and stachyose are prominent examples of chickpea galactosides (Jana et al., 2018; Rex et al., 2020; Yan et al., 2022). Polysaccharides serve as either storage or structural carbohydrates within chickpea plants.

Starch

Starch, the most abundant polysaccharide in chickpeas, typically makes up 33%–55% of their content depending on the variety (Aguilera, Esteban, et al., 2009; Alajaji & El-Adawy, 2006; Chavan et al., 1987; Mathew et al., 2022). Starch is concentrated in the cotyledons and, in contrast to protein, is less abundant in their outer edges. This helps explain the observations that cotyledon cells on the outer periphery contain fewer starch granules (or none at all) compared to cells within the core cotyledon, where they are more ubiquitous (Wood et al., 2014). Approximately 96% of the total starch in whole Desi chickpea seeds was enzyme-susceptible starch, compared to 94% present in whole Kabuli chickpea seeds (Wood et al., 2014). Starch is less abundant in cells of the outer periphery of cotyledons in both Desi and Kabuli chickpea. Notably, chickpea starch has a distinctively high amylose content, ranging between 23% and 35% (Ghoshal & Kaushal, 2020), with some variations between varieties. Desi types often exhibit slightly higher amylose content than Kabuli (Singh et al., 2004). Amylose forms crystalline structures resistant to the digestive enzymes within the human body. Unlike amylose, amylopectin is readily digested by humans and other mammals. Amyloses contribute to the overall functionality of chickpea starch in various food applications. In this regard, the relatively high amylose content contributes to several beneficial properties of chickpea (Foster-Powell et al., 2002; Sandhu & Lim, 2008). One key advantage of chickpea starch is its relatively low GI. This translates to a slower and more controlled release of glucose into the bloodstream compared to other starches. Additionally, chickpea starch contains resistant starch, a type of dietary fiber that reaches the large intestine undigested and acts as a prebiotic (Christl et al., 1992; Foster-Powell et al., 2002; Sandhu & Lim, 2008). While resistant starch offers numerous health benefits, it can also contribute to flatulence in some individuals. This occurs when gut bacteria ferment the starch in the large intestine, producing gas (Kaur & Prasad, 2021). Crystallinity, a measure of the ordered structure within the starch granules, also plays a crucial role. Chickpea starch is primarily characterized as type C crystallinity and exhibits a moderate crystallinity (12.03%–27.60%), indicating a less rigid structure compared to some other starches (Shahzad et al., 2019). This translates to easier digestibility and potentially slower retrogradation, extending the shelf life of starch-based products (Huang et al., 2007).

Given the unique chemical and functional properties, chickpea starch stands out as a valuable ingredient in diverse applications (Faridy et al., 2020). Starch plays a crucial role in extrusion cooking, acting as the primary contributor to the desired crunchy and expanded texture of the final product. Furthermore, chickpea starch finds applications in gluten-free baking, where it serves as a binder and provides structure to baked goods (dos Santos Kanai et al., 2023; Lu et al., 2022).

Dietary Fiber

Chickpeas are also rich in dietary fiber, offering potential health advantages such as reduced risk of heart disease, diabetes, obesity, and certain cancers (Brummer et al., 2015; Jukanti et al., 2012; Marlett et al., 2002; Sandhu et al., 2023). Dietary fiber consists of poly/oligosaccharides and other plant-based materials. Chickpeas contain both soluble and insoluble fibers (Kaur & Prasad, 2021). There are several classification systems for dietary fiber. In this review, the classification is based on its ability to dissolve in a solution mimicking human digestive enzymes (Tungland & Meyer, 2002). Soluble fiber slows down digestion in the colon, forming a gel that binds cholesterol and sugars. This process can contribute to lowering blood cholesterol and blood sugar levels. In contrast, while insoluble fiber is not directly absorbed by the body, it adds bulk to stool and keeps things moving smoothly through the digestive system. Additionally, it also encourages the growth of beneficial gut bacteria (Clemente & Olias, 2017; Hayyat et al., 2023; Liu et al., 2024). The total dietary fiber (TDF) content of chickpeas is around 17–27 g per 100 g of raw chickpea seed. The soluble (SDF) and insoluble (IDF) dietary fibers are about 1–5 and 12–20 g per 100 g of raw chickpea seed, respectively (Table 4) (Aguilera, Martín-Cabrejas, et al., 2009; Candela et al., 1997; Perez-Hidalgo et al., 1997). The insoluble fiber mainly comprises cellulose, hemicellulose, and lignin. SDF includes oligosaccharides, pectin, and β-glucans (Brummer et al., 2015; Rodríguez et al., 2006).

The fiber content is primarily concentrated in the cell walls (Sandhu et al., 2023). The cotyledon cell walls of Desi chickpeas are composed of cellulose coated and/or

TABLE 4 Dietary fibers content in chickpea seeds (g/100 g).

Dietary fibers	Aguilera, Martín-Cabrejas, et al., 2009	Perez-Hidalgo et al., 1997	Candela et al., 1997
		Kabuli	
IDF	20.5	12.6	23.5
SDF	1.0	5.0	4.3
TDF	21.4	17.6	27.8
IDF:SDF	21:1	–	–

Abbreviations: IDF, insoluble dietary fiber; SDF, soluble dietary fiber; TDF, total dietary fiber.

cross-linked with xyloglucan, embedded within a significant pectic matrix. This matrix comprises galacturonans (including both rhamnogalacturonan and homogalacturonan), arabinan, and arabinogalactan, possibly including arabinogalactan proteins (Wood et al., 2018). In general, plant tissue softening during cooking occurs due to the weakening or dissociation of intermolecular connections between cells through solubilization, depolymerization, and/or the loss of pectic polysaccharides (Wood et al., 2018). Starch gelatinization also takes place at temperatures above 70°C, with significant implications for digestibility and cooking processes. The gelatinization temperature is influenced by moisture content and the structural characteristics of the starch granules (Du et al., 2023). Figure 5 shows the effect of cooking chickpeas at a temperature above the gelatinization point, where under polarized light, starch birefringence is no longer visible. In the bright-field images on the left, the starch granules display more amorphous characteristics, as their shapes are less uniform.

A study investigated the relationship between the hard-to-cook defect (a condition where pulse seeds hydrate but do not soften even after prolonged cooking) and genetic and environmental factors affecting cotyledon composition in mature Desi chickpeas. The authors showed that formation of hard-to-cook chickpea may involve interactions among divalent ions (like calcium and magnesium), phytates, and pectic polysaccharides. The same group of researchers proposed a model whereby sub-epidermal cotyledon cell walls in hard-to-cook chickpea phenotypes contain lower levels of homogalacturonan methyl-esterification, thereby allowing more prevalent calcium-mediated associations between pectin molecules and formation of stronger cell walls (Wood et al., 2018). This may explain some differences between the slow-cooking and fast-cooking chickpea phenotypes. Chickpeas possess an equal or higher dietary fiber content than other pulses (Jukanti et al., 2012). Desi chickpea varieties tend to have a higher TDF and IDF content than Kabuli types, primarily due to their thicker seed coats (Rincón et al., 1998).

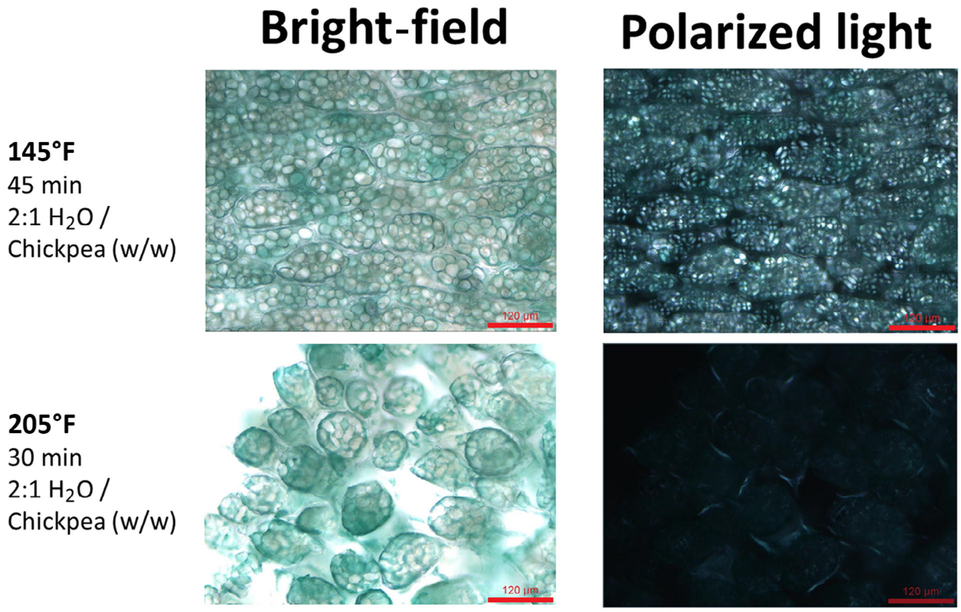

FIGURE 5 Starch gelatinization and loss of birefringence in chickpea cotyledon cells cooked at 145°F (below Chickpea's starch gelatinization temperature) and 205°F (above chickpea's starch gelatinization temperature). All the pictures/panels in Figure 5 are unpublished material created internally in PepsiCo.

3.1.2 | Major proteins in chickpeas

Chickpeas are an excellent source of protein, with a protein content ranging from 21% to 24% across various genotypes. Chickpeas have consistently demonstrated higher protein content compared to some other pulses. In developing Asian and African countries, protein–energy malnutrition is a prevalent issue among young children and infants, adversely affecting their health due to insufficient energy and protein intake. Pulses, a significant component of the Afro-Asian diet, can play a crucial role in alleviating malnutrition by providing a higher protein percentage (Iqbal et al., 2006).

Chickpea protein is present in the cotyledon's parenchyma tissue as a continuous matrix within the cell. Cotyledon protein is slightly more concentrated in the cotyledon periphery adjacent to the seed coat (Wood et al., 2014). The protein content of Desi and Kabuli chickpeas can vary depending on several factors, including the environment where they are grown, the agricultural practices used, and the specific genotypes (Khan et al., 1995). It was reported that Kabuli varieties of chickpea had a range of crude protein content from 23.38% to 25.90%, while Desi varieties had a range of 23.68% to 25.57% (Medeiros et al., 2023; Singh & Jambunathan, 1981). A study by Kaur et al. compared the protein content of cultivated and wild chickpea, finding that Desi varieties had the highest average content (25.31%), followed by Kabuli (24.67%) and wild species (24.30%) (Kaur et al., 2019). Additionally, research suggests that the digestibility of protein in raw chickpeas increases from around 89.01% to 96.94% after heating (Bekele et al., 2021). This variation in protein digestibility is attributed to factors such as chickpea variety, processing methods, and antinutritional factors. Processing methods such as soaking, cooking, and autoclaving can improve the digestibility of the protein by denaturing protein structures. Notably, cooking can also inactivate compounds that hinder protein absorption, such as trypsin inhibitors (Begum et al., 2023; Singh & Jambunathan, 1981). Chickpeas contain four main protein classes: albumins (8%–12%), globulins (53%–60%), glutelins (19%–25%), and prolamins (3%–7%) (Day, 2013; Grasso et al., 2022) (Table 5).

Albumins

Albumins are water-soluble proteins that make up 8%–12% of total proteins in chickpeas (Begum et al., 2023; Hall et al., 2017). They are rich in essential amino acids, particularly those containing sulfur. This makes them nutritionally valuable (Liu et al., 2008). They play a vital role in chickpea growth due to their various enzymatic and metabolic functions (Clemente et al., 2000). While albumins offer considerable nutritional value, albumins also contain antinutritional compounds like amylase and trypsin inhibitors. These inhibitors can potentially interfere with the digestion of other proteins and carbohydrates (Boye, Zare, et al., 2010). As albumins are soluble in water, they enhance the foaming properties of chickpea and facilitate interaction with starch, impacting the functionality of chickpea protein ingredients (Day, 2013; Grasso et al.,

TABLE 5 Protein classes in chickpeas (Begum et al., 2023; Hall et al., 2017).

Protein class	Content (% of total protein)	Solubility	Protein	Svedberg unit	No. of subunit (polypeptide)
Globulin	53–60	Salt soluble	Legumin	11S	6
			Vicilin	7S	3
Albumin	8–12	Water soluble	–	–	2
Glutelin	19–25	Soluble in dilute acid or alkali detergents	–	–	–
Prolamin	3–7	Alcohol soluble	–	–	–

2022). Albumins contribute to smoothness, viscosity, and emulsification in food systems. They can also influence the foaming and whipping properties of chickpea-based products (Clemente et al., 2000).

Globulins

Globulins are the most abundant class in chickpea, comprising 53%–60% of chickpea protein (Begum et al., 2023; Hall et al., 2017). Globulins are soluble in dilute salt solution and serve as the primary storage protein for the plant. They significantly contribute to the foaming and emulsifying properties of chickpea flour (Guldiken et al., 2022; Shevkani et al., 2019). However, albumin also plays a significant role in these properties as it can exhibit superior emulsion stability compared to globulin (Ye et al., 2024). Additionally, it has been found that albumin can have higher foaming capacity (FC) than globulin at certain pH levels (Higa et al., 2024). Globulin consists of two major components, that is, legumin (11S) and vicilin (7S) proteins (Boukid, 2021), classified based on their sedimentation coefficients (Day, 2013). Legumin (11S) is a large oligomeric protein with a molecular weight ranging from 320 to 400 kDa. It is composed of six polypeptide subunits ($\alpha\beta$, 54–60 kDa each), linked by disulfide bonds (Boukid, 2021). Vicilin (7S) is a trimeric protein with a smaller molecular weight of 145–190 kDa. It has a simpler structure than legumin and lacks cysteines, and therefore, it does not contain disulfide bonds (Chang et al., 2012). Globulins majorly contribute to the cohesiveness, gelation, and WHC (important for textural stability in products like hummus and tofu). Their interactions with other proteins and starch influence overall texture (Rachwa-Rosiak et al., 2015).

Glutelin

Chickpea proteins are particularly rich in glutelin compared to other pulses (Chang et al., 2012). Glutelins make up 19% to 25% of chickpea proteins and are soluble in reducing salts, bases, acids, and detergents (Rachwa-Rosiak et al., 2015). Glutelins have higher concentrations of cysteine and methionine, which are two essential amino acids for human health (Chang et al., 2012). Glutelin has also been found to accumulate selenium when chickpea seeds are germinated in the presence of sodium selenite, and selenized glutelin emulsions have shown increased stability and cellular antioxidant activity (Hernández-Grijalva et al., 2022). Overall, chickpea glutelin has potential applications as a food ingredient due to its functional properties and nutritional benefits. Unlike globulins that form gels, glutelin forms a network of elastic fibers, providing desirable bite and chewiness to products like chickpea-based sausages and meat alternatives (Grasso et al., 2022; Kyriakopoulou et al., 2021; Mokni Ghribi et al., 2018; Vinod et al., 2023).

Prolamins

Prolamins are alcohol-soluble proteins that make up 3%–7% of the protein in chickpeas. They are rich in glutamine and proline (Grasso et al., 2022; Rachwa-Rosiak et al., 2015). Their presence aligns with other pulse proteins, which generally lack sufficient sulfur-containing amino acids (Santos et al., 2017). Prolamins generally have poor foaming and emulsifying properties, potentially contributing to the weaker emulsifying and foaming abilities observed in cereal flours compared to legume flours, which are rich in albumins and globulins (Stone et al., 2019).

Amino acid composition in chickpea proteins

Chickpeas contain all nine essential amino acids, but they vary in quantities (Table 6) (Iqbal et al., 2006). Chickpeas are notable for their relatively high content of glutamic acid, aspartic acid, and arginine. In comparison, methionine and cysteine are present in smaller quantities within chickpea seeds (Boye, Aksay, et al., 2010; Day, 2013). Notably, chickpea flour has a significantly higher essential amino acid content (39.89 g/100 g of protein) than wheat flour (32.20 g/100 g of protein) (Begum et al., 2023).

A study by Singh and Jambunathan (1981) explored the distribution of amino acids across different chickpea protein fractions. Lysine, arginine, glutamic acid, aspartic acid, and leucine stand out as the most abundant amino acids across all fractions, highlighting their crucial role in seed protein structure and function. Albumin generally shows the highest level of essential amino acids like lysine, leucine, and tyrosine, suggesting its importance

TABLE 6 Amino acid composition of chickpea seed protein and its protein fractions.

Amino acids	Whole seed g/16 g N[a]	Whole seed g/16 g N[b]	Albumin g/16 g N[b]	Globulin	Glutelin	Prolamin
Essential amino acids						
Cystine	1.3	1.3	3.5	1.0	1.4	0.6
Lysine	7.7	6.2	10.8	6.6	6.8	2.3
Isoleucine	4.1	4.5	5.1	4.4	5.4	2.3
Leucine	7.0	7.6	9.8	7.5	9.1	1.6
Methionine	1.6	1.1	1.8	0.8	1.2	0.9
Phenylalanine	5.9	5.5	5.1	6.1	4.4	3.4
Threonine	3.6	4.0	5.4	3.5	5.7	2.2
Tryptophan	1.1	–	–	–	–	–
Valine	3.6	5.0	4.5	4.2	5.7	2.1
Nonessential amino acids						
Alanine	4.4	4.0	5.3	4.3	4.9	2.3
Arginine	10.3	10.9	5.6	10.7	6.8	4.8
Aspartic acid	11.4	12.2	13.8	12.7	10.1	10.3
Glutamic acid	17.3	16.3	18.4	15.2	16.6	17.7
Glycine	4.1	4.1	5.4	3.7	4.7	3.1
Histidine	3.4	2.7	2.3	2.6	2.9	2.6
Proline	4.6	4.0	4.9	5.2	4.8	7.2
Serine	4.9	5.5	5.2	5.2	5.6	1.9
Tyrosine	3.7	2.8	4.2	2.9	3.7	2.3

[a]Alajaji and El-Adawy (2006).
[b]Singh and Jambunathan (1982).

for early seedling growth and development. Globulin, on the other hand, is richer in arginine and glutamic acid, potentially contributing to stress tolerance and storage. Glutelin and prolamin, the major storage proteins, are dominated by glutamine and proline, reflecting their role in energy reserves and protein stability. Notably, cystine, methionine, and tyrosine are relatively low in all fractions, suggesting potential limitations in these essential amino acids for seed nutrition. This detailed breakdown of amino acids provides valuable insights into their nutritional profile and the specific contributions of different protein fractions (Singh & Jambunathan, 1981). Although methionine and cysteine are found in low concentrations in chickpea (Begum et al., 2023), consuming pulses along with cereals can overcome these amino acid deficiencies and meet an individual's dietary requirements (Langyan et al., 2022).

3.1.3 | Fats

Chickpeas contain a relatively high amount of fat compared to other pulses such as peas, mung beans, and cowpeas, ranging from 4.1 to 6.0 g/100 g (Koul et al., 2022). However, chickpeas do not have enough fat to be considered an oilseed, like soybean, rapeseed, and sunflower. These lipids primarily exist as triacylglycerols (TAGs), phospholipids (PhLs), sterols, steryl esters, and free fatty acids (FFAs). A compositional study reported that chickpea fat exhibited 17%–20% PhLs and 56%–67% TAGs (Zia-Ul-Haq et al., 2007). TAG serves as a biosynthetic precursor and energy source during seed germination, while PhL acts as membrane lipids (Jukanti et al., 2012). The fatty acid profile of chickpea reveals a diverse range of lipids with distinct health implications. While saturated fatty acids (SFAs) like palmitic acid and stearic acid make up 13.88–16.51 g/100 g, the majority of fats are unsaturated, with monounsaturated fatty acids (MUFAs) like oleic acid dominating at 25.72–36.78 g/100 g and polyunsaturated fatty acids (PUFAs) like linoleic acid accounting for a whopping 49–58 g/100 g (Xiao et al., 2023) (Table 7). This abundance of PUFAs, particularly linoleic acid, contributes to the potential role of chickpeas in reducing cardiovascular disease risk. Levels of up to 2.4% of alpha-linolenic acid (ALA), an omega-3 PUFA, have been reported for chickpea seeds (Ryan et al., 2007), although significantly less than linoleic acid, as shown in Table 7. On average, oleic and linoleic acids are relatively higher in Kabuli and Desi

TABLE 7 Fatty acid composition (g/100 g total fat) of chickpeas (Ryan et al., 2007; Xiao et al., 2023).

Fatty acids	Range	Fatty acids	Range
Myristic (C14:0)	0.15–0.21	*cis*-11-Eicosenoic (C20:1)	0.56–0.66
Pentadecanoic (C15:0)	0.05–0.07	Heneicosanoic (C21:0)	0.04–0.06
Palmitoleic (16:1)	0.19–0.28	Behenic (C22:0)	0.39–0.47
Palmitic (C16:0)	10.35–12.23	Tricosanoic (C23:0)	0.03–0.06
Heptadecanoic (C17:0)	0.05–0.08	Lignoceric (C24:0)	0.09–0.17
Oleic (C18:1)	24.81–35.98	SFA	13.88–16.51
Stearic (C18:0)	1.58–2.19	MUFA	25.72–36.78
Linoleic (C18:2)	49.30–58.18	PUFA	49.34–58.20
α-Linolenic (C18:3)	0.03–2.41	USFA	83.49–86.12
Arachidic (C20:0)	0.78–0.97	USFA/SFA	5.06–6.21

Abbreviations: MUFA, monounsaturated fatty acid; PUFA, polyunsaturated fatty acid; SFA, saturated fatty acid; USFA, unsaturated fatty acid.

types, respectively. Both linoleic and alpha-linolenic acids are essential fatty acids crucial for various physiological functions, growth, and overall well-being (Jukanti et al., 2012; Xiao et al., 2023). The abundance of unsaturated fatty acids in chickpeas makes them an exceptional legume from a nutritional standpoint. This composition can vary among varieties, with brown and black chickpeas generally containing more PUFAs than beige varieties (Summo et al., 2019). The fatty acid profile is important as it influences factors like texture, shelf life, flavor, aroma, and overall nutritional value of chickpea-based food products.

3.2 | Micronutrients in chickpea

3.2.1 | Minerals

Chickpea, a nutritious legume, is rich in various minerals, including potassium, phosphorus, calcium, magnesium, sodium, zinc, iron, boron, manganese, and copper (Swamy, 2023). The mineral content of chickpea can vary depending on the cultivar and location of cultivation. Among the minerals, potassium, phosphorus, magnesium, and calcium are found in higher concentrations in chickpea (Erbaş Köse & Mut, 2020). Notably, chickpeas are a good source of potassium, phosphorus, magnesium, and calcium. They are also recognized for their high iron and zinc content, which can help in combating micronutrient malnutrition (Thavarajah & Thavarajah, 2012). The mineral composition of chickpeas is provided in Table 8. Minerals are distributed specifically and selectively throughout the kernel, showing selective localization in the seed coat and cotyledon (see Figure 6). For instance, in Kabuli chickpeas, calcium is rich in the seed coat, especially in the hypodermis layer, where it plays a crucial role in pectin binding. This is facilitated by a calcium-mediated mechanism that involves the dimethyl-esterification of pectins by pectin methyl-esterase (PME), allowing for the formation of calcium–pectin cross-links that contribute to the structural integrity of the cell wall (Wood et al., 2018). Magnesium, on the other hand, is less concentrated in the hypodermis. Potassium is mostly located in the cotyledon and is almost absent in the seed coat. Phosphorus has a similar behavior as well. Sulfur is evenly distributed in both seed coat and cotyledon. In cotyledons, potassium, magnesium, phosphorus, and sulfur coexist, indicating the presence of protein. Wild chickpea species generally contain higher levels of manganese, magnesium, and calcium compared to cultivated varieties (Rajasekhar et al., 2022). Desi and Kabuli chickpeas exhibit no significant differences in mineral content, except for calcium, which is found in slightly lower concentrations in Kabuli chickpeas as compared to Desi chickpeas (Begum et al., 2023).

3.2.2 | Vitamins

Chickpeas are not only rich in minerals but also a good source of various vitamins, encompassing both fat-soluble and water-soluble types. They provide fat-soluble vitamins, such as vitamins E and K, and water-soluble vitamins, such as vitamin A, B-complex vitamins (including B1, B2, B3, B5, B6, and B9), and vitamin C (Koul et al., 2022). Chickpeas are an excellent source of vitamin B6, which is crucial for energy metabolism, brain function, and immune system health. A single cup of cooked chickpeas provides about 14% of the daily recommended intake (DV) of vitamin B6. Another essential B vitamin, folate, is also abundant in chickpeas and plays vital role in DNA synthesis and cell division (Jukanti et al., 2012; Wallace et al., 2016). In addition, chickpeas offer other vitamins like A, C, and E (Table 9). Vitamin A contributes to vision, immune function, and cell growth, while vitamin C acts as an antioxidant, protecting cells from damage and

TABLE 8 Minerals profile (mg per 100 g) of chickpeas.

Minerals	Chavan et al., 1987	Alajaji & El-Adawy, 2006	Wang et al., 2010 Desi and Kabuli	Jukanti et al., 2012	Wallace et al., 2016	Koul et al., 2022
Macro-elements						
Calcium	93–159	176	81–165	80–226	57	57–160
Sodium	9.8–150	121	–	21–24	24	24
Potassium	692–10.28	870	994–1060	816–1580	718	700–718
Magnesium	91–168	176	147–169	115–212	79	79–138
Phosphorus	244–458	226	394–451	294–828	252	250–310
Microelements						
Iron	3.0–10.6	7.72	4.5–5.5	4.3–7.6	4.31	4.0–12.3
Zinc	1.5–4.2	4.32	3.4–4.1	2.8–5.6	2.76	2.76–4.1
Manganese	–	2.11	3.3–3.8	1.2–4.8	21.31	–
Copper	0.6–1.7	1.10	–	0.5–1.40	0.66	–

supporting immune function and collagen production (Koul et al., 2022; Wood & Grusak, 2007). Vitamin E, another antioxidant, plays a role in immune function and maintaining blood vessel health (Khadim & Al-Fartusie, 2021; Meydani & Blumberg, 2020).

3.3 | Phytochemicals

Aside from essential nutrients, chickpeas are also a good source of various phytochemicals with potential health benefits due to their antioxidant and anti-inflammatory properties. These phytochemicals include flavonoids, alkaloids, polyphenols, tannins, isoflavones, anthocyanins, steroids, and others (Faridy et al., 2020; Keyimu et al., 2020) and are believed to have evolved as a defense mechanism against environmental threats like parasites, fungi, insects, and herbivores (Rachwa-Rosiak et al., 2015). Among the notable phytochemicals in chickpeas are polyphenols such as phenolic acids, flavonoids, and so forth. Pérez-Ramírez et al. (2023) reported a total of 24 polyphenol compounds across three different chickpea varieties, indicating the versatility of phenolic profile in chickpeas. Polyphenols are potent antioxidants associated with the reduction of various chronic diseases (Wang et al., 2021). Darker chickpeas generally contain higher levels of these compounds, enhancing their antioxidant capacity (Segev et al., 2010). Isoflavones are the main bioactive components of sprouted chickpea seeds. Zhao et al. (2009) detected seven isoflavones in sprouted chickpea seeds, including biochanin A, calycosin, formononetin, genistein, trifolirhizin, ononin, and sissotrin, among which, biochanin A and formononetin were the prominent ones, while the other five isoflavones contributed to smaller quantities. These isoflavones may play a role in reducing the risk of chronic diseases like heart disease, cancer, and neurodegenerative disorders (Jukanti et al., 2012; Wood & Grusak, 2007). Phenolic acids, another class of phytochemicals present in chickpeas, also demonstrate antioxidant properties and can chelate metal ions, further contributing to health benefits (Segev et al., 2010). Studies such as Kaur et al. (2019) have identified flavonoids, phenolic acids, and condensed tannins as major phenolic compounds in chickpeas, highlighting their role in scavenging and eliminating reactive oxygen species from the bloodstream. Chickpeas also contain beneficial carotenoids, a group of lipid-soluble antioxidants/pigments, which are responsible for the bright color of the seeds and offer antioxidant and provitamin A properties, potentially preventing various human diseases (Mathew et al., 2022). Carotenoids are broadly categorized into two types: hydrocarbon carotenoids, which include α-carotene, β-carotene, and lycopene, and oxygenated carotenoids, known as xanthophylls, such as lutein, zeaxanthin, violaxanthin, and β-cryptoxanthin (Ashokkumar et al., 2014; Wang et al., 2021). Lutein (7.70 µg/g) was reported as the major source of carotenoids in chickpea seeds, followed by zeaxanthin (5.76 µg/g), β-carotene (0.40 µg/g), and violaxanthin (0.05 µg/g). In comparison, Desi chickpea cultivars generally exhibited higher average levels of total carotenoids (16.80 µg/g) than Kabuli varieties (12.33 µg/g) (Ashokkumar et al., 2014).

4 | ANTINUTRITIONAL FACTORS IN CHICKPEAS

Although chickpeas are considered to be one of the most nutritious pulses, they also contain several antinutritional factors such as enzyme inhibitors (protease and amylase),

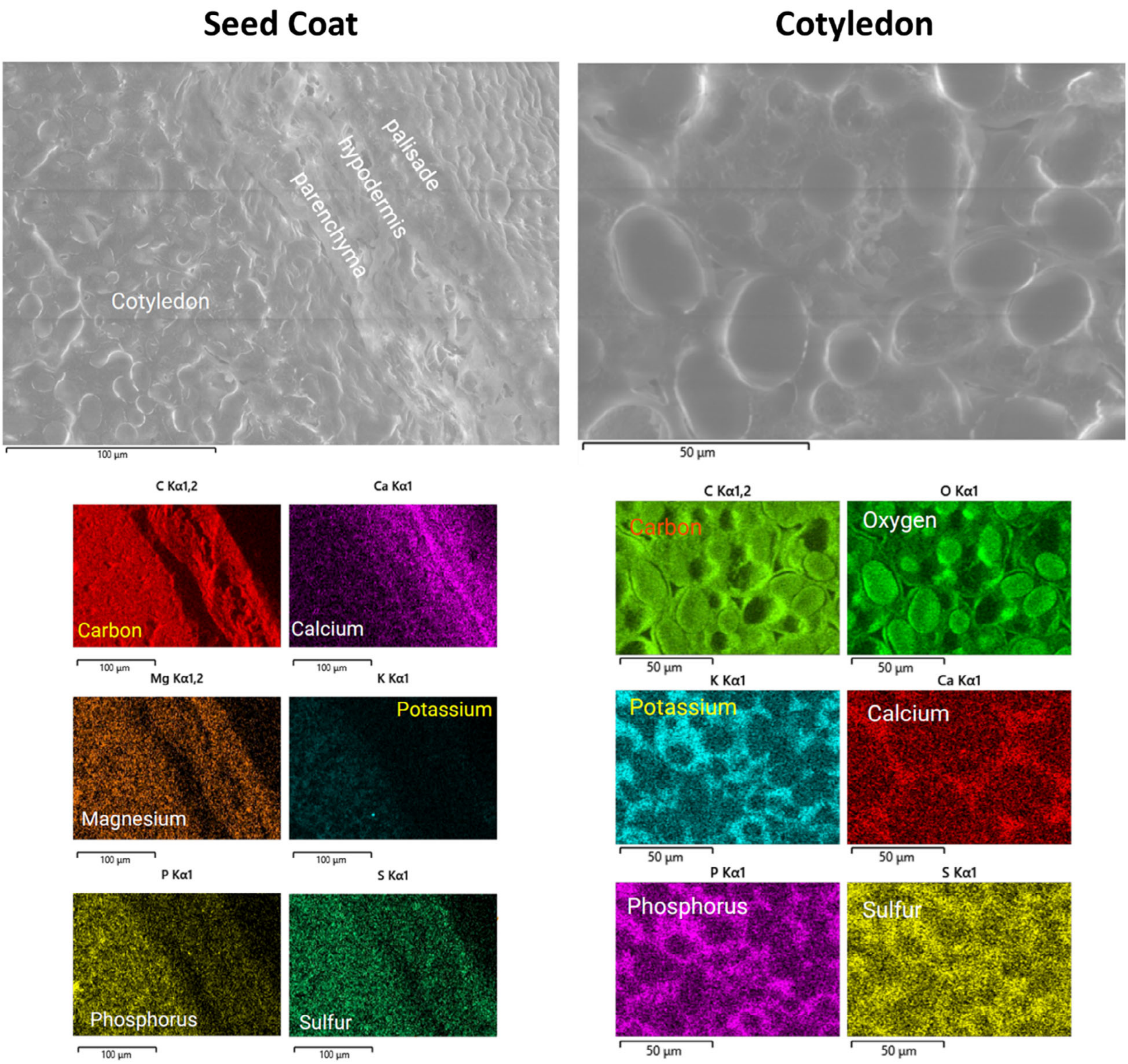

FIGURE 6 Tissue-specific mineral distribution in the seed coat and cotyledon for kabuli chickpeas characterized through scanning electron microscopy and energy-dispersive X-ray spectroscopy. All the pictures/panels in Figure 6 are unpublished material created internally at PepsiCo.

TABLE 9 Vitamin profile (per 100 g) of chickpeas.

Vitamins	Jukanti et al., 2012	Wallace et al., 2016	Koul et al., 2022
Vitamin A: β-Carotene (µg)	40–46	67	67
Vitamin B1: Thiamine (mg)	0.03–0.48	0.48	0.45–0.5
Vitamin B2: Riboflavin (mg)	0.15–0.30	0.21	0.20–0.26
Vitamin B3: Niacin (mg)	1.22–2.90	1.5	1.54–2.00
Vitamin B5: Pantothenic acid (mg)	1.02–1.59	1.6	1–2
Vitamin B6: Pyridoxine (mg)	0.30–0.55	0.54	0.30–0.38
Vitamin B9: Folate (mg)	150.557	0.56	206–290
Vitamin C: Ascorbic acid (mg)	1.34–6.00	4.0	–
Vitamin E: Tocopherols (mg)	1.91–22.0	0.82	11.2–12.9

TABLE 10 Antinutritional factors present in chickpea seeds.

Antinutritional factors **Enzyme inhibitors (units/mg)**	**Jukanti et al., 2012**	**Mathew et al., 2022**
Trypsin	6.7–14.6	10.9–12.32
Chymotrypsin	2.79–9.40	7.1–13.01
Amylase inhibitor	0.0–8.70	0.05–8.70
Phyto lectin	400	180–400
Polyphenols (g/kg)		
Total phenols	0.16–0.61	0.64–3.03
Tannins	0.0–4.85	4.85–5.10
Phytic acid	1.21	5.8–12.1
Oligosaccharides (g/kg)		
Raffinose	–	2.3–14.5
Stachyose	–	5.8–25.6
Verbascose	–	1.9–7.2
Saponins (g/kg)	0.40–5.6	9.1–17.0

lectins, polyphenols (tannins and phenols), oligosaccharides (raffinose, stachyose, and verbascose), and others like cyanogenic glycosides, hemagglutinins, and saponins (El-Adawy, 2002) that could limit their consumption and the nutritive utilization of their proteins (Table 10). These compounds potentially hinder digestion, nutrient intake, and absorption and may even discourage overall consumption and other negative effects (Mahmood et al., 2017).

4.1 | Polyphenols

Chickpeas contain natural chemical compounds like polyphenols, which act as a defense mechanism against insects and other predators. These molecules interact with proteins, carbohydrates, and minerals via noncovalent interactions in the digestive system of human and animals to reduce the digestibility of protein, carbohydrates, and minerals within the plant (Wallace et al., 2016). Tannins are a specific type of polyphenols associated with antinutritional properties, including reduced digestibility and potential negative health effects (Sharma et al., 2021). They can bind to proteins and other macromolecules, including amino acids and alkaloids, forming insoluble complexes that hinder digestion and nutrient absorption (Muzquiz & Wood, 2007). This effect is particularly significant for legumes, as they naturally contain high levels of tannins. In addition, the presence of tannins can adversely affect protein quality in legumes. They inhibit digestive enzymes like amylase, lipase, trypsin, and chymotrypsin, leading to decreased protein digestibility and utilization. Additionally, tannins can interfere with iron absorption, further impacting nutritional value (Sharma et al., 2021; Wang et al., 2010).

Certain processing methods can help reduce their polyphenol contents. Studies have shown that autoclaving, a high-pressure steam sterilization technique, can effectively decrease polyphenol levels in chickpeas by roughly 21%–31% (Jood et al., 1987). Similarly, sprouting the seeds for 48 h has also been found to have a significant impact, lowering polyphenol content by 19%–28% (Khattak et al., 2007; Mathew et al., 2022). The total phenolic content in chickpeas varies widely, ranging from 0.64 to 3.03 g/kg of seeds. Tannins also present in varying amounts, with traces detected in some varieties and up to 5.1 g/kg in others, as shown in Table 10.

4.2 | Phytic acid

Phytic acid, a phosphorus storage form in chickpeas, can bind to minerals like calcium, zinc, and iron, thus potentially hindering their absorption by the body (Zia-Ul-Haq et al., 2007). However, research suggests that phytic acid may also offer potential health benefits like anticancer and cholesterol-lowering effects (Lee et al., 2007; Shamsuddin, 2002). Additionally, lower phytic acid content enhances protein solubility, especially at acidic pH (Cheryan & Rackis, 1980; Mondor et al., 2004; Selle et al., 2000). Chickpeas contain relatively lower levels of phytic acid as compared to other legumes, while the amount of phytic acid present in chickpeas varies significantly, typically ranging from 5.8 to 12.1 g/kg of seeds (Table 10). Conventional processing methods including soaking, cooking, and germination, as well as novel processing techniques such as irradiation, ultrasound, and high pressure, could effectively degrade phytic acid (Sarkhel & Roy, 2022).

4.3 | Protease inhibitors

Chickpeas are known to contain protease inhibitors, particularly trypsin and chymotrypsin inhibitors. The Desi variety generally exhibits higher levels of protease inhibitors compared to Kabuli, which impacts their nutritional value and applications in food products (Singh & Jambunathan, 1982; Wati et al., 2010). These molecules play a crucial role in the defense of the plant against various environmental stressors. However, in humans, they can potentially hinder protein digestion by blocking proteolytic enzymes (Gupta et al., 2017). The amount of these inhibitors can vary, with trypsin inhibitor activity ranging from 10.9 to 12.3 IU/mg and chymotrypsin inhibitor activity ranging between 7.1 and 13.0 IU/mg (Table 10). Specifically, trypsin inhibitors interfere with trypsin activity, affecting protein breakdown (Birk, 1993). Food processes like heating or boiling can significantly reduce their activities (Alajaji & El-Adawy, 2006). It was also noted that freezing chickpea seeds at −80°C for 24 h could successfully inactivate chymotrypsin inhibitors (Sarkhel & Roy, 2022).

4.4 | Amylase inhibitors

Chickpeas, like other legumes, contain amylase inhibitors. These molecules act as a natural defense against insects by hindering the activity of amylase enzymes, limiting their ability to digest starch (Kaur et al., 2014). While these inhibitors primarily target pancreatic amylase in humans, they might cause slight starch digestion inhibition, especially with uncooked seeds. Fortunately, boiling chickpeas for just 10 min completely deactivates this inhibitor (Singh, 1988). Interestingly, research suggests potential benefits associated with these bioactive compounds. Their ability to regulate starch digestion holds promise for managing blood glucose levels and preventing rapid sugar spikes (Sievenpiper et al., 2009). Across different chickpea varieties, reported amylase inhibitor activity varies significantly, ranging from 0.05 to 8.7 IU/mg, as shown in Table 10.

4.5 | Phytolectins (hemagglutinins)

Lectins, also known as hemagglutinin, are glycoproteins that bind to a specific sugar, which can cause red blood cell agglutination, leading to digestive issues like diarrhea, bloating, and vomiting (Gupta et al., 2017). However, the lectins found in chickpeas are generally considered to be of low concern for human health. This is because their toxicity levels are typically low, and they are easily deactivated by heat, making them safe to consume (Singh, 1988). In fact, cooking completely destroys them, while germination can drastically reduce their activity (by up to 77%) (El-Adawy, 2002). Studies have reported that the amount of lectin in chickpeas can vary widely, ranging from 180 to 400 units/mg (Table 10).

4.6 | Oligosaccharides

Chickpeas contain oligosaccharides like raffinose and stachyose, but our bodies lack the enzyme needed to digest them. This leads to fermentation by gut bacteria in the large intestine, causing gas and bloating (Elango et al., 2022). Stachyose is the most abundant oligosaccharide in chickpeas (Sreerama et al., 2012). Simple methods like soaking for 24 h and cooking can significantly reduce these sugars. Soaking removes about 66% of raffinose and up to 50% of stachyose, while germination is even more effective for their removal (Mahmood et al., 2017). Studies have shown that raffinose content in chickpeas can range from 2.3 to 14.5 g, stachyose from 5.8 to 25.6 g, and verbascose from 1.9 to 7.2 g/kg of seeds (Table 10).

4.7 | Cyanogenic glycosides

Chickpeas contain cyanogenic glycosides, which play a major role in their natural defense mechanisms. When plant tissues are damaged, these compounds release hydrogen cyanide, which can be toxic in high amounts (Tiku, 2018). However, the concentration of cyanogenic glycosides in chickpeas is very low (around 0.02 g/kg), making them safe for human consumption. Moreover, common processing methods such as soaking and cooking effectively eliminate these compounds from chickpeas (Mathew et al., 2022).

4.8 | Saponins

Saponins are another type of compound found in chickpeas, consisting of a complex mixture of pentacyclic triterpenoid glycosides (Wang et al., 2021). They can interact with cell membranes and potentially exhibit toxicity in high doses (Rao & Koratkar, 1997). Chickpeas were reported to contain mainly soyasaponin, with soyasaponins βg (VI) and Af being the major saponins, followed by soyasaponins Ba (V) and αg across different varieties (Pérez-Ramírez et al., 2023). Saponin content in chickpeas can vary between 9.1 and 17 g/kg of seeds (Table 10). Literature data showed that processing methods resulted in diverging effects on saponins. Cooking significantly reduces saponin levels in chickpeas (El-Adawy, 2002). In contrast, Milán-Noris et al. (2023) found slightly decreased total saponin content (TSC) in soaked Desi cultivars and notably increased TSC in cooked samples compared to their raw counterparts. Therefore, the influence of food processing on saponins needs to be carefully evaluated for functional food development.

5 | TECHNOFUNCTIONAL PROPERTIES OF CHICKPEA PROTEINS

Chickpea proteins exhibit various technofunctional properties that influence their behavior during processing, storage, and consumption (Grasso et al., 2022). Chickpea proteins possess a remarkable array of technofunctional properties that make them attractive for various food and industrial applications. These properties, crucial for determining protein behavior during processing, storage, and consumption, encompass solubility, f, oil-holding capacity

(OHC), emulsifying properties, foaming properties, gelling properties, and textural properties (Day, 2013). In addition, other factors also influence the technofunctional properties of protein, including their amino acid profile and noncovalent interactions (Kumar et al., 2021, 2023, 2024), which determine their structure and conformation, as well as processing conditions such as pH, temperature, and interactions with other counterparts (Zayas, 1997). Some reported values for these technofunctional properties are summarized in Table 11. Furthermore, the study by Wang et al. (2022) highlights the impact of chickpea flour and yellow pea concentrate on the expansion, texture, and overall quality of extruded food products, reinforcing the significance of chickpea proteins' technofunctional properties in food applications.

5.1 | Solubility

Solubility is a crucial technofunctional property of proteins, determines how well proteins dissolve in water (Zayas, 1997). Chickpea proteins demonstrate high solubility within specific pH ranges, with optimal solubility typically observed between pH 1–3 and 7–10 (Ghribi et al., 2015). However, solubility drastically decreases at their isoelectric point (around pH 4.5), owing to weakened electrostatic repulsion and hydration (Table 11) (Bessada et al., 2019; Boye, Zare, et al., 2010; Day, 2013; Kaur & Singh, 2007; Sánchez-Vioque et al., 1999; Withana-Gamage et al., 2011). Various studies have been carried out on ionic strength and temperature influences on the solubility of chickpea proteins. Increasing salt concentration (e.g., NaCl) to a certain level can improve solubility ("salting-in" effect) for some chickpea proteins, while temperature changes have complex effects depending on the specific protein fractions and processing conditions (Ramani et al., 2021). Understanding these factors is crucial for maximizing the utilization of chickpea proteins. Hong et al. (2024) investigated the effects of varying cooking temperatures on chickpea flour and protein properties. The authors noted that water boiling at 96°C significantly decreased the solubility of chickpea flour from 39.45 to 25.21 g/100 g flour, along which, the chickpea proteins denatured and polymerized, resulting in a marked decrease in albumin- and globulin-like protein fractions, while simultaneously increasing the proportion of glutelin-like fractions (Hong et al., 2024). Several strategies have been explored to improve solubility, such as enzymatic and chemical modifications (del Mar Yust et al., 2013; Yust et al., 2010).

5.2 | Water-holding capacity

WHC is a crucial technofunctional property that describes the ability of protein to retain water against gravity via physicochemical interactions (Table 11). This ability depends heavily on the structure and conformation of the protein. Hydrogen bonding plays a key role, as hydrophilic groups on the protein side chains (e.g., imine, amino, carboxyl, hydroxyl, carbonyl, and sulfhydryl) interact with water molecules (Ramani et al., 2021; Zayas, 1997). WHC significantly impacts food applications, influencing the texture and mouthfeel of products containing protein ingredients. High WHC can lead to efficient water retention, contributing to the moistness and softness of the product. On the other hand, low WHC, or the failure of chickpea protein to bind water, can result in dry, brittle products, particularly during storage (Boye, Zare, et al., 2010; Singhal et al., 2016).

The study conducted by Withana-Gamage et al. (2011) reported WHC values ranging from 2.34 to 4.31 g/g, with Kabuli varieties exhibiting higher WHC compared to Desi varieties. Furthermore, WHC was positively correlated with protein content and emulsion stability, underscoring its significance in food applications (Withana-Gamage et al., 2011). Chickpea proteins exhibit varying WHC values depending on processing methods and cultivar differences (Kaur & Singh, 2007; Toews & Wang, 2013). In a study, chickpea protein isolates were investigated using freeze drying and refractive window (RW) drying methods. The RW-dried isolates exhibited significantly higher WHC (4.26 g/g) in comparison to freeze-dried samples (3.17 g/g) (Tontul et al., 2018), suggesting that drying methods can significantly affect WHC, with potential applications in food formulations requiring water retention (Boye, Aksay, et al., 2010; Ghribi et al., 2015; Kaur & Singh, 2007). Processing intensity, such as temperature and duration, also plays a crucial role in protein techno-functionality. Mesfin et al. (2021) observed that roasting chickpea at 150°C increased WHC due to protein denaturation, which unfolded the protein structure and exposed more hydrophilic groups, thereby enhancing WHC. However, at a higher roasting temperature of 180°C, WHC decreased, likely due to the transition of polypeptide chains into random coils, reducing the availability of hydrophilic sites for water binding (Mesfin et al., 2021). These findings highlight the importance of processing conditions on optimizing protein techno-functionality for food applications.

TABLE 11 Technofunctional properties of chickpea proteins: Protein solubility (PS), water-holding capacity (WHC), oil-holding capacity (OHC), emulsion activity index (EAI), emulsion stability index (ESI), foaming capacity (FC), foaming stability (FS), and least gelation concentration (LGC).

Protein description	PS (%)	WHC (g/g)	OHC (g/g)	EAI (m^2/g)	ESI (min)	FC (%)	FS (%)	LGC (%)	Reference
Isoelectric precipitation and freeze drying	94.2 (pH 11); 2 (pH 5)	3.17	3.65	26.00 (pH 2); 44.13 (pH 10)	5.3 (pH 2); 40.6 (pH 10)	37.00 (pH 2); 24.25 (pH 10)	10.25 (pH 2); 8.25 (pH 10)	–	Tontul et al., 2018
Isoelectric precipitation and refractance window drying	74.5 (pH 12); 5 (pH 6)	4.26	3.15	16.69 (pH 2); 38.16 (pH 10)	518.6 (pH 2); 6.1 (pH 10)	33.75 (pH 2); 23.00 (pH 10)	3.75 (pH 2); 11.75 (pH 10)	–	
Isoelectric precipitation	88–90 (pH 7); 19–20 (pH 4.5)	2.3–3.4	2.08–3.96	–	–	30.4–44.3	–	14–18	Kaur & Singh, 2007
Isoelectric precipitation (Desi/Kabuli varieties)	2–6 (pH 4.1–4.4); 90 (pH 6)	2.34–4.31	3.06–5.74	Kabuli: 1.13–1.30 Desi: 0.88–1.15	Kabuli: 20.3–26.7; Desi: 19.3–21.4	–	–	–	Withana-Gamage et al., 2011
Desi (isoelectric precipitation)	60 (pH 2.0); 75 (pH 10); 2 (pH 5)	3.05	1.3	5.7	19.5	106	32	14	Boye, Aksay, et al., 2010
Desi (ultrafiltration)	65 (pH 2.0); 64 (pH 10); 2 (pH 5)	2.60	1.22	5.5	20	100	12	10	
Kabuli (isoelectric precipitation)	–	3.10	1.20	5.7	19.4	106	33	14	
Kabuli (ultrafiltration)	–	2.50	1.40	5.45	20	103	18	10	

5.3 | Oil-holding capacity

OHC plays a crucial role in food formulation, alongside WHC, by influencing texture, mouthfeel, and overall structure (Singhal et al., 2016). This capacity stems from lipid–protein interactions, where hydrophobic, electrostatic, hydrogen, and noncovalent interactions form between protein side chains and TAGs in oils. The size of protein powder particles also affects OHC, with smaller and less dense particles offering more surface area for oil absorption and entrapment compared to larger, denser ones (Zayas, 1997). Chickpea protein isolates have OHC ranging from 2.1 to 4.0 g/g similar to soy and bean protein isolates (Kaur & Singh, 2007). Interestingly, they observed that Kabuli chickpeas have higher OHC than Desi varieties (approximately 4.0 and 2.1–3.7 g/g, respectively). Tontul et al. (2018) reported an OHC of 3.15–3.65 g/g for chickpea protein isolates, suggesting their suitability for oil-rich foods like sausages, dairy products, and salad dressings. These isolates also contributed to flavor retention, palatability, and extended shelf life (Tontul et al., 2018). It is worth mentioning that freeze-dried chickpea protein isolates have higher OHC compared to RW-dried samples (Ghribi et al., 2015; Gong et al., 2016). This phenomenon is attributed to the enhanced hydrophobic properties in freeze-dried samples (Ghribi et al., 2015). Additionally, protein aggregation and disulfide bond formation during RW drying might have contributed to the lower OHC in these isolates (Tontul et al., 2018). Further, the effects of processing methods on OHC vary among chickpea cultivars. For instance, germination decreased the OHC of the Arerti cultivar (Kabuli type) while increasing it in the Natoli cultivar (Desi type), indicating that cultivar-specific responses to processing methods influence protein techno-functionality (Mesfin et al., 2021).

5.4 | Emulsifying properties

Emulsifying properties are essential for food proteins, as they help stabilize oil-in-water mixtures and prevent separation and droplet aggregation. These properties are highly influenced by factors like amino acid composition, molecular weight, and structure. Key parameters for assessing emulsifying ability include emulsifying capacity (EC; oil volume emulsified per gram of protein) and emulsifying activity index (EAI; maximum interfacial area covered by a stabilized emulsion per gram of protein). Additionally, the emulsifying stability index (ESI) evaluates the resistance of the emulsion to structural changes over time (Boye et al., 2010; Zayas, 1997).

Kabuli chickpea isolates tend to have higher emulsifying activity and stability indices than Desi isolates (Withana-Gamage et al., 2011), attributed to the superior film-forming ability. Chickpea protein concentrate (CPC) also exhibits higher emulsifying values compared to pea and lentil concentrates, with a slight advantage for Kabuli chickpea (Boye, Zare, et al., 2010). Additionally, the method of drying affects emulsion stability, with conventional drying methods yielding more stable emulsions compared to freeze drying due to partial protein denaturation (Boye, Aksay, et al., 2010; Ghribi et al., 2015; Karaca et al., 2011; Tontul et al., 2018) (Table 11). However, different drying methods may lead to distinct protein structures, impacting emulsifying abilities (Gong et al., 2016). Extraction methods also significantly influence protein emulsifying properties. Superior EC, EAI, and ESI were reported in chickpea protein isolates extracted by isoelectric precipitation compared to those obtained via salt extraction. This improvement is linked to the higher surface charge and solubility observed in the former isolates (Karaca et al., 2011).

5.5 | Foaming properties

Foaming properties are another important technofunctional aspect of food protein. These properties enable proteins to act as surfactants, stabilizing air bubbles in various formulations, which enhances texture and sensory attributes (da Silva Ramos & Vidigal, 2022; Van den Wouwer et al., 2025). Two key metrics assess this ability: foaming capacity (FC), measuring the volume increase achieved through whipping, and foaming stability (FS), determining how well the foam retains its volume over time (Day, 2013; Ramani et al., 2021). Different protein fractions within chickpea exhibit varying foaming properties, with albumin generally performing better than globulin. Studies have shown that the FC of chickpea cultivars ranges from 30% to 44%, similar to other pulse varieties (Table 11). Defatted CPCs exhibit even higher capacity (201%–228%), though lower than some pulses (Kaur & Singh, 2007; Toews & Wang, 2013). Chickpea flours have low foam volume but high stability (over 90% after 2 h), attributed to their water-soluble compounds (Kaur & Singh, 2007). Chickpea protein isolates, on the other hand, have been reported to have FC values ranging from 3.75% to 37.00% and FS values between 0% and 11.75% (Tontul et al., 2018). The variations in FC and FS largely depend on processing conditions and solution factors. Ma et al. (2023) applied high-pressure homogenization (HPH) to treat chickpea protein isolate and found enhanced FC and FS of chickpea protein when treated at pressures up to 90 MPa for one to two cycles, but these properties declined as the pressure increased further. This variation probably resulted from the destroyed balance between the hydrophobic and charged polar groups of the chickpea protein molecules caused by higher pressure, disrupting the equilibrium required for optimal film and foam formation at the gas–liquid interface (Ma et al., 2023).

5.6 | Gelling properties

Gelling properties are particularly important for globular proteins in food applications. These proteins can form gels when heated in water. This process involves protein denaturation and rearrangements (Day, 2013), resulting in a gel network with unique properties (Zayas, 1997). The temperature at which gels form, and the resulting gel properties are closely associated with the protein molecular structure, as well as protein–protein and protein–solvent interactions (Day, 2013). The minimum gelling concentration (MGC) refers to the lowest amount of protein required to form a gel. Chickpea protein isolates have higher least gelling concentrations (14%–18%) compared to their flours (10%–14%), attributed to variations in protein composition and nonprotein components (Kaur & Singh, 2007). Interestingly, Kabuli chickpea flour forms firmer gels at lower concentrations (10%) than Desi flours, linked to differences in protein and nonprotein constituents (Boye, Aksay, et al., 2010). Several factors like protein concentration, pH, and processing methods influence gelation behavior (Schmidt, 1981). The least gelation concentration (LGC) of chickpea protein exhibited pH-dependent behavior. When heated chickpea protein slurries at 90°C for 30 min followed by incubating at 4°C overnight, chickpea protein displayed the lowest LGC (8%) at pH 7, followed by higher LGC values (12%) at pH 3 and 9. Interestingly, no gels were formed when chickpea protein was heated at concentrations below 20% at pH 5 (near the isoelectric point [pI]), which was attributed to the weaker interactions between proteins and water molecules caused by the near-zero net charge of the protein at pI, reducing its ability to form a stable gel network (Tang et al., 2023). In addition, it has also been observed that variation in gelation also depends on the extraction techniques (Papalamprou et al., 2009). The authors observed significantly higher LGC (11.5%) of chickpea protein prepared by isoelectric precipitation compared to those obtained via ultrafiltration (LGC, 5.5%). This variation was likely due to the gentler nature of the dialysis isolation method, which preserved protein structure better than the isoelectric precipitation method did (Papalamprou et al., 2009).

5.7 | Textural properties

Chickpea proteins exhibit superior textural properties compared to some other legume proteins, attributed to their unique surface behavior and structural characteristics (Soto-Madrid et al., 2023). Studies reveal that chickpea proteins, particularly the globulin fraction, have enhanced surface hydrophobicity and interfacial properties, leading to improved texture in chickpea-based products like curds (Soto-Madrid et al., 2023). This is due to their higher 11S protein content (Nguyet et al., 2021). Further studies show that incorporating CPC into “Merguez” sausages (Mokni Ghribi et al., 2018) enhances protein content and processing yield. Sausages with CPC additions exhibit improved texture and overall acceptability, suggesting CPC as a valuable protein source for enhancing the quality of meat products.

6 | CHEMICAL AND TECHNOFUNCTIONAL PROPERTIES OF CHICKPEA STARCH

Chickpea starch, the major carbohydrate in chickpea seeds, exhibits diverse technofunctional properties valuable in various applications (Goñi & Valentıń-Gamazo, 2003; Miao et al., 2009). Chickpea starch granules exhibit variability in size, with kabuli chickpeas typically having larger granules than Desi chickpeas. The starch granules range in size from 2 to 35 μm in length and from 1 to 14 μm in width (Table 12) (Ghoshal & Kaushal, 2020; Miao et al., 2009; Singh et al., 2004). The swelling power of chickpea starch ranges between 11.61 and 13.28 g/g at 85°C, indicating its WHC during gelatinization (Table 12). The solubility of chickpea starch varies between 13.2% and 14.9%, demonstrating the portion of starch that dissolves in water under specified conditions (Rincón-Londoño et al., 2016). Moreover, its syneresis ranges from 6.9% to 46.83%, highlighting the ability of starch to retain water during freeze–thaw cycles. Chickpea starch exhibits a notable water binding capacity, ranging from 77.8% to 92.25%, indicating its efficacy in binding water molecules. The pasting properties of chickpea starch encompass a wide spectrum, with peak viscosity ranging from 1107 to 4174 cP (Table 12), while breakdown viscosity, final viscosity, setback, and pasting temperature vary across different varieties.

Differential scanning calorimetry (DSC) analysis reveals gelatinization temperatures of chickpea starch between approximately 59 and 67°C and enthalpy values (ΔH) ranging from 1.2 to 8 J/g, elucidating the energy involved in the gelatinization process (Rincón-Londoño et al., 2016). Starch granules, once tightly packed, begin to swell and

TABLE 12 Variability in physicochemical (amylose content), structural (granule size and length), physical (swelling power, solubility, syneresis, water binding capacity [WBC]), and functional (pasting properties like peak viscosity [PV], breakdown viscosity [BV], final viscosity [FV], setback and pasting temperature [PT], and gelatinization [DSC]) properties of starches from different chickpea cultivars.

Variety		Kabuli	Desi	PDG-5	BG-1076	Canada chickpea varieties	Indian chickpea varieties
Starch granule		Oval, size: 7–29 µm; Kabuli is larger than desi		Large oval to small spherical shape, length: 2–30 µm, width: 3–10 µm		Oval to spherical, size: 5–35 µm	Oval to spherical, length: 17.0–20.1 µm, width: 1.0–14.4 µm
Amylose content (%)		31.80	35.24	30.2	31.3	33.9–40.2	28.6–34.3
Crystallinity (%)		13.12	12.03	–	–	31.3–34.4	–
Crystalline type		C	C	–	–	C	C
Swelling power		11.61 g/g at 85°C	13.28 g/g at 85°C	11.92	12.11	14.50–17.80 g/g at 80°C	11.4–13.6 g/g
Solubility (%)		13.72	14.50	13.47	13.53	–	13.2–14.9
Syneresis (%)		42.45 for freeze–thaw stability	46.83 for freeze–thaw stability	–	–	–	6.9–18.5 for 24–120 h
WBC (%)		88.72	92.25	87.91	89.91	–	77.8–89.4
Pasting property	PV (cP)	2823	1989	–	–	3223–4174	1107–2173
	BV (cP)	857	1164	–	–	394–1308	–
	FV (cP)	3375	4685	–	–	5939–7147	1639–3250
	Setback (cP)	3117	3172	–	–	3110–4281	532–1123
	PT (°C)	73.4	70.7	–	–	67.98–70.48	75.1–77.1
DSC (gelatinization)		T_0: 62.24°C, T_p: 67°C, ΔH: 1.87 J/g	T_0: 59.4°C, T_p: 68.83°C, ΔH: 1.2 J/g	T_0: 66.5°C, T_p: 77.1°C, ΔH: 15.6 J/g	T_0:65.6°C, T_p: 69.6°C, ΔH: 14.8 J/g	T_0: 58.65–59.83°C, T_p: 63.29–65.51°C, ΔH: 11.16–13.01 J/g	T_0: 61.5–64.8°C, T_p: 66.4–69.0°C, ΔH: 7.2–8.7 J/g
References		Miao et al., 2009		Ghoshal & Kaushal, 2020		Hughes et al., 2009	Singh et al., 2004

transform into a gel, a crucial step in thickening sauces, binding ingredients, and creating the textures that are favored by consumers in various foods. Chickpea starch exhibits relatively low gelatinization temperatures compared to other starches. This characteristic makes it easier to cook with and potentially more readily digestible by our bodies (Shahzad et al., 2019; Singh et al., 2004).

As we attempt for a more sustainable future, chickpea starch emerges as a promising option. Its cultivation requires less water and fertilizer compared to other starch sources, like corn or wheat, making it an environmentally friendly choice. Research is ongoing to understand how chickpea variety, environmental factors, and processing techniques influence its properties. It is reported that chickpea starch underwent significant decreases in resistant starch in response to soaking and cooking, which was accompanied with a notable increase in the available starch content, suggesting that part of the resistant starch is modified by heat during cooking and is converted into digestible starch (Yolanda et al., 2009). The diverse chemical and functional properties of chickpea starch, influenced by its amylose content, crystallinity, granule size, and molecular characteristics, contribute to its versatility in various food, pharmaceutical, and industrial applications.

7 | APPLICATION OF CHICKPEAS

Chickpeas have been extensively studied for their technofunctional properties, potential health benefits, and valuable food ingredients (Shevkani et al., 2019). Their prominence in the word cloud, highlighting its potential as a nutrient-rich crop, with keywords like "protein," "vitamins," "dietary," and others, and emphasizing its contribution to human health, was generated using RStudio, as shown in Figure 7. Beyond its nutritional value, chickpeas hold promise in diverse applications such as food systems, bioactive compounds, and others. Their seed properties make them ideal for food products and protein ingredients, while their nutraceutical properties are being explored for potential therapeutic treatments. The word cloud reveals a multifaceted legume with immense potential. From nourishing diets to bioactive compounds and other health benefits, chickpeas are a valuable resource for a growing population. This section explores the appli-

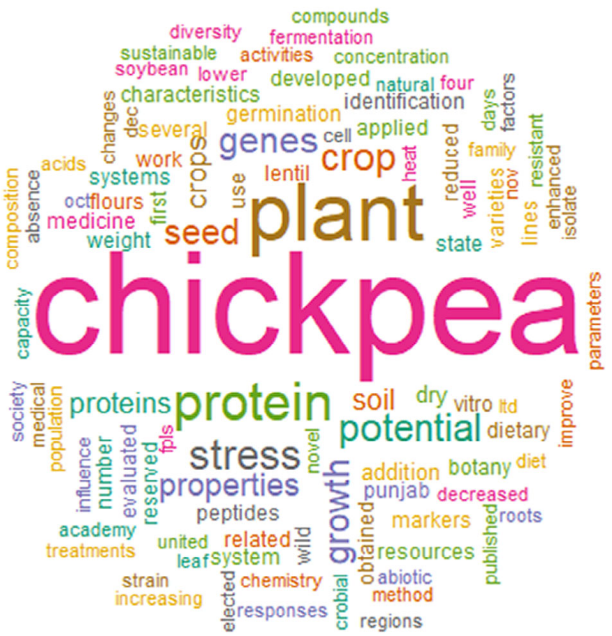

FIGURE 7 Word cloud of terms associated with chickpea research, generated from a collection of scientific abstracts.

cations of chickpeas and the uses of their co-products, showcasing their economic and nutritional benefits.

7.1 | Whole chickpea in food systems

7.1.1 | Traditional and historic food uses of chickpea

Chickpea boasts a remarkable diversity in its culinary applications, appearing in countless dishes across various cultures (Mustafa & Reaney, 2020; Singh & Jambunathan, 1981). Its longstanding use in traditional cuisines speaks to its versatility, serving as both a main component and supporting ingredient in various meals. While young, green chickpeas harvested 10–15 days before maturity are enjoyed as a vegetable, mature chickpeas offer a multitude of options. Whole chickpeas can be soaked, boiled, germinated, or roasted, with each method unlocking unique textures and flavors. Chickpea splits, also known as chana dal, is a popular type of dal made by dehulling and splitting chickpeas (Singh & Jambunathan, 1981; Wood & Malcolmson, 2021). The term “dhal” has a rich history, appearing in ancient Sanskrit texts and being recognized for its nutritional value by early Indian medical practitioners like Charaka and Sushruta (Nene, 2006). This enduring popularity reflects the importance of pulses as a source of protein, fiber, and essential nutrients in the Indian diet. Chickpea flour, often called besan in India, plays a starring role in countless traditional dishes (Chavan et al., 1987). Its versatility shines in batters, pastes, and doughs, shaping delectable creations like fluffy boondi dumplings for savory snacks, spongy dhokla cakes for a healthy breakfast, crispy pakoras for irresistible fritters, and spicy bhujia for a flavorful garnish (see Figure 8). Beyond savory treats, besan even lends its texture and nutty flavor to delightful sweets (Wood, Knights, et al., 2011).

The flour of roasted chickpea is also known as Sattu, and it is consumed as a drink in summer and is popular for its cooling properties and versatility. In addition, it can also be blended with milk to create a soothing slurry, which is often enjoyed by those experiencing digestive discomfort like ulcers. Its low cost and abundance of nutrients make it a valuable staple for many, particularly those facing economic challenges (Dabas, 2005; Satusap et al., 2014). Physical and thermal properties of Sattu are influenced by its moisture content and particle size, with higher moisture content affecting flowability but increasing thermal conductivity (Raigar & Mishra, 2015).

7.1.2 | Contemporary, modern, and future food uses of chickpea

The nutritional ability of chickpea flour is extending beyond traditional cuisines. Its incorporation into pasta, cookies, biscuits, and even dairy products like yogurt enhances their nutritional value while offering gluten-free alternatives (Altaf et al., 2021). Studies have shown that pasta enriched with 25% chickpea flour can lower the GI while increasing protein, fat, and mineral content (Goñi & Valentıń-Gamazo, 2003; Padalino et al., 2015). Chickpea flour also finds applications in making puffed snacks and crisps. In addition, recent research suggests that using legume flours in baked goods like pasta, biscuits, and bread can reduce their in vitro glycemic response, opening up exciting possibilities for developing new products suitable for those on low-glycemic diets (Monnet et al., 2019). Furthermore, chickpea flour, with enhanced nutritional and physicochemical properties in response to various food processing methods, has shown expanded applications in food products. For instance, conventionally processed chickpea flour (soaking + boiling + drying) was successfully integrated into *Mankoushe Zaatar*, a popular Lebanese pastry, where it improved both the nutritional quality and sensory acceptability by reducing off-flavors typically associated with chickpea flour (Dandachy et al., 2019).

The rise of veganism has fueled the demand for plant-based milk alternatives. Chickpea, with its rich nutritional profile, emerges as a promising contender for developing meal replacement beverages (Bampidis & Christodoulou, 2011). Chickpea–coconut blends offer superior protein

FIGURE 8 Traditional dishes containing chickpeas.

and calcium content compared to other plant-based milk substitutes (Rincon et al., 2020). Additionally, fresh and fermented chickpea beverages show potential as soy and cow milk alternatives (Wang et al., 2018).

The versatility of chickpea flour extends beyond traditional uses. In yogurt production, it acts as a prebiotic and thickening agent, enhancing viscosity, antioxidant activity, and probiotic viability, leading to a healthier and more functional yogurt (Hussein et al., 2020). Beyond its delicious appeal, chickpeas offer a wealth of health benefits, with studies linking their consumption to reduced risk of chronic diseases (Duranti, 2006; Murty et al., 2010; Wood & Grusak, 2007). Being rich in protein, dietary fiber, bioactive compounds, and antioxidants, with a low GI, chickpeas truly qualify as a functional food (Crujeiras et al., 2007).

7.2 | Chickpea proteins

Chickpea protein ingredients have established themselves in various food applications, including cereals, bakery items, infant formulas, and even meat alternatives. However, their potential extends beyond food, offering promising possibilities in the nutraceutical field as well (Boye, Zare, et al., 2010; Shevkani et al., 2019). Incorporating chickpea protein into cereals and baked goods can enhance their protein content and overall nutritional value and sometimes even improve certain organoleptic and sensory characteristics. For example, partially substituting wheat flour with chickpea protein can significantly increase the protein content and nutritional value of baked goods like pasta, bread, and cookies. In some cases, it can even improve their texture and taste (Dandachy et al., 2019; Garcia-Valle et al., 2021; Rachwa-Rosiak et al., 2015; Summo et al., 2019).

CPC also demonstrates potential in improving food properties. In "Merguez" sausage, it enhances organoleptic properties, reduces fat oxidation, and improves color stability (Mokni Ghribi et al., 2018). Studies suggest chickpea protein in bread can increase dough volume due to its high WHC (Aider et al., 2012). In addition, chickpea proteins improve surface properties compared to ovalbumin, making them a potential alternative to animal proteins in food formulations (Soto-Madrid et al., 2023).

Chickpea protein even shows promise in infant nutrition. Malunga et al. (2014) reported on infant formulas using chickpea protein from different varieties. Their developed formula meets the World Health Organization (WHO) nutritional requirements with minimal additional ingredients. To minimize factors, the chickpeas underwent treatments like germination and dehulling. More recently, Kyriakopoulou et al. (2021) highlighted that chickpea protein has emerged as a potential soy alternative in meat substitutes due to its excellent gelling, emulsification, and foaming properties. Additionally, new chickpea-based yogurt alternatives incorporating CPC are appearing in the market.

Beyond food applications, chickpea proteins hold promise in the nutraceutical sector. For instance, chickpea protein isolates can be used as capsules for micronutrient delivery, like folate (Karunaratne et al., 2017). Their biocompatibility and nutritional value make them suitable candidates for further exploration in this area. Moreover, the innovative use of chickpea flour, as demonstrated by Wang et al. (2023), in creating high-quality protein expanded extrudates from corn meal and yellow pea concentrate underscores the versatility of chickpea proteins in enhancing the physical properties of food products.

7.3 | Chickpea fiber and starch

Chickpea protein extraction often involves removing the seed hull and separating starch and fiber. These fractions offer a treasure trove of benefits. Chickpea hulls are rich in dietary fiber and polyphenols, making them ideal for animal feed, food additives, and even textile dyes (Tassoni et al., 2020). Niño-Medina et al. extracted fiber from chickpea hulls and incorporated it into bread, improving sensory characteristics, calcium content, and antioxidant activity due to the phenolic compounds (Niño-Medina et al., 2017, 2019). The potential of these phenolic compounds has also been explored as natural antioxidants in meat products, offering a sustainable alternative to synthetic options (Kanatt et al., 2011; Kumar et al., 2015). Jose et al. (2019) took it a step further by extracting textile dyes from chickpea hulls, creating a more environmentally friendly way to color cotton, wool, and silk clothing. Chickpea starch, separated during protein enrichment, boasts unique physicochemical properties like low swelling power and suitable pasting behavior. This makes it ideal for controlled swelling applications in sauces and dressings (Miao et al., 2009; Singh et al., 2004). Additionally, its gluten-free nature makes it a valuable ingredient for pasta and noodles (Jagannadham & Parimalavalli, 2015).

7.4 | Aquafaba

The cooking or canning liquid of chickpeas, known as aquafaba, shines as an egg white alternative. Its high moisture content (92%–95%) and presence of soluble and insoluble fibers, proteins (0.9%–1.5%), and phenolic compounds make it an excellent foaming agent (Mustafa & Reaney, 2020). Buhl et al. (2019) demonstrated its successful use in food foams and emulsions, even exceeding egg white in some cases. The functional properties of aquafaba depend on factors like chickpea variety, processing methods, and additional ingredients. Further research in this area can unlock its full potential in food product development.

7.5 | Bioactive peptides in chickpea: Health benefits and potential applications

Bioactive peptides are specific protein fragments released from parent proteins through enzymatic or acid/base hydrolysis, exhibiting diverse beneficial health effects (Du & Li, 2022; Du et al., 2022; Du, Cao, et al., 2023; Milán-Noris et al., 2018). These peptides are typically less than 3 kDa in size and contain two to 20 amino acids. Their biological activity exhibits diverse functionalities depending on their amino acid sequence. Studies suggest that food-derived peptides, in general, can scavenge free radicals, protect against cell damage, and offer additional health benefits like cholesterol reduction (Aguilar-Toalá et al., 2022; Naeem et al., 2022). These peptides can also act as natural antioxidants in food preservation and functional food development (de Castro & Sato, 2015).

Studies have identified various bioactive peptides in chickpeas. For instance, chickpea albumin-derived peptides exhibit antioxidant activity, inhibit cancer cell proliferation, and lower cholesterol and triglyceride in mice (Kou et al., 2013; Xue et al., 2015, 2018). Besides, chickpea globulin-derived peptides demonstrate free radical scavenging and cell protection against oxidative damage (Torres-Fuentes et al., 2015). The amino acid composition of these peptides is crucial for their bioactivity. Peptides rich in specific amino acids, like leucine, proline, and aspartic acid, tend to have stronger antioxidant activity (Wali et al., 2021). Enzymatic hydrolysis can further enhance their activity. Studies have identified specific chickpea peptides with potent antioxidant properties, effective in scavenging free radicals and protecting cells (Gupta et al., 2017).

A study by Chandrasekaran et al. (2020) identified several peptides from chickpea hydrolysates that showed promise in inhibiting key enzymes that are related to type 2 diabetes. Specifically, the peptides were found to inhibit dipeptidyl peptidase-IV (DPP-IV), which is involved in glucose metabolism, as well as α-amylase and α-glucosidase, both of which aid in the digestion of carbohydrates (Chandrasekaran et al., 2020). In another study, chickpea albumin-derived peptides (FEI, FEL, FIE, FKN, FGKG, and MEE by their amino acid one-letter codes) were found to exhibit potent antidiabetic effects, which suggested promising therapeutic potential of chickpea hydrolysates and the identified peptides (Quintero-Soto et al., 2021). However, further research is needed to evaluate the individual activity of these peptides and their potential applications. Recently, a study was carried out by isolating three peptide sequences from germinated chickpea protein: SPGAGKG, GLAR, and STSA (by their amino acid one-letter codes). The researchers found that the SPGAGKG peptide was the most active inhibitor of both DPP-IV and α-glucosidase (Chandrasekaran & Gonzalez de Mejia, 2022). Inhibiting these enzymes can help slow down the absorption of glucose into the bloodstream, which can improve blood sugar control. In addition, chickpea protein hydrolysates obtained from Desi varieties have demonstrated significant angiotensin-converting enzyme (ACE) inhibitory activity, highlighting their potential as natural antihypertensive agents. This activity is primarily attributed to bioactive peptides released during enzymatic hydrolysis, which enhance the functional and therapeutic properties of chickpeas. These peptides interact with ACE, inhibiting its activity and subsequently lowering blood pressure (Gupta & Bhagyawant, 2019; Gupta et al., 2022). Enzymatic hydrolysis using enzymes such as alcalase and flavorzyme has been shown to optimize the release of these peptides, thereby enhancing their ACE inhibitory effects (Gupta & Bhagyawant, 2019). In vivo studies further highlight the antihypertensive benefits of chickpea-derived peptides, showing significant reductions in systolic and diastolic blood pressure in hypertensive models (Gupta et al., 2022). Further research is needed to investigate the efficacy of specific chickpea peptides in animal models and clinical trials. Overall, these studies highlight the potential of chickpea protein hydrolysates as a source of bioactive peptides with various health benefits, including antioxidant, antidiabetic, antihypertension, and anticancer properties.

8 | CONCLUSIONS AND FUTURE PERSPECTIVES

Chickpeas offer a diverse array of nutritional and functional benefits, making them a valuable addition to human health and food science. In this review, we comprehensively explored various facets of this legume, including its chemical/microstructural composition, macronutrients, micronutrients, phytochemicals, functional properties, and potential applications. Chickpeas boast a remarkable nutritional profile, being rich in protein, dietary fiber, essential minerals, vitamins, and phytochemicals. Notably, their high protein content makes them particularly valuable for vegetarians and vegans. Chickpea proteins exhibit remarkable functional properties, including solubility, WHC/OHC, emulsification, foaming, and gelation. These properties make chickpeas valuable for food development, allowing for the development of various value-added products. These products can be beneficial for individuals suffering from protein–energy malnutrition and those with gluten intolerance. While these contribute to various health benefits, proper processing is essential to optimize nutrient bioavailability. Derived from chickpea proteins, bioactive peptides show promise in areas such as anti-inflammatory, antidiabetic, and antioxidant effects, among others, opening avenues for nutraceutical and therapeutic applications.

Future research efforts should focus on mitigating antinutritional factors while preserving beneficial phytochemicals. Exploring chickpea protein functionality in diverse food applications, such as meat alternatives, bakery products, and functional beverages, can unlock their commercial potential. Investigating specific health benefits of bioactive peptides can lead to the development of novel functional foods and nutraceuticals. Understanding the healthy ingredients in chickpeas and how they work, as well as exploring the synergistic effects and mechanisms of actions of these bioactive molecules and proteins, is key to unlocking their full potential. This knowledge can be used to develop new, nutritious foods and supplements enriched with chickpeas or their health-promoting components using advanced proteomics, genomics, artificial intelligence, and machine learning techniques. By focusing on these critical areas, future research can help chickpeas play a powerful role in promoting health and well-being.

AUTHOR CONTRIBUTIONS

Nandan Kumar: Conceptualization; methodology; investigation; validation; formal analysis; visualization; writing—original draft; writing—review and editing. **Shan Hong**: Methodology; investigation; formal analysis; writing—review and editing. **Yi Zhu**: Conceptualization; methodology; investigation; resources; writing—review and editing; data curation. **Antonio Garay**: Methodology; data curation; investigation; resources; writing—review and editing. **Jun Yang**: Investigation; resources; writing—review and editing. **Douglas Henderson**: Investigation; resources; writing—review and editing. **Xin Zhang**: Investigation; resources; writing—review and editing. **Yixiang Xu**: Investigation; resources; writing—review and editing. **Yonghui Li**: Conceptualization; methodology; investigation; supervision; funding acquisition; resources; project administration; writing—review and editing.

ACKNOWLEDGMENTS

This is Contribution No. 25-043-J from the Kansas Agricultural Experiment Station. This work was in part supported by the USDA Agricultural Research Service Non-Assistance Cooperative Project (Grant Accession No. 443993). Yi Zhu, Antonio Garay, Jun Yang, Douglas Hen-

derson, and Xin Zhang are/were employed by PepsiCo, Inc. The views expressed in this manuscript are those of the authors and do not necessarily reflect the position or policy of PepsiCo, Inc. Yixiang Xu is employed by the US Department of Agriculture (USDA). Mention of trade names or commercial products in this publication is solely for the purpose of providing specific information and does not imply recommendation or endorsement by USDA. USDA is an equal opportunity provider and employer.

CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

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How to cite this article: Kumar, N., Hong, S., Zhu, Y., Garay, A., Yang, J., Henderson, D., Zhang, X., Xu, Y., & Li, Y. (2025). Comprehensive review of chickpea (*Cicer arietinum*): Nutritional significance, health benefits, techno-functionalities, and food applications. *Comprehensive Reviews in Food Science and Food Safety*, *24*, e70152. https://doi.org/10.1111/1541-4337.70152