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Review Article

Effect of Sustainable Pretreatments on the Nutritional and Functionality of Chickpea Protein: Implication for Innovative Food Product Development

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Chickpea is a globally cultivated legume, rich in vitamins, protein, carbohydrates, polyphenols, fatty acids, fibers, and flavonoids. Despite its nutritional benefits, chickpeas contain antinutritional factors that can hinder nutrient absorption. Therefore, we reviewed the various pretreatment methods to enhance chickpea protein's nutritional value and functional properties. Thermal and biochemical treatments and food applications of chickpea protein are thoroughly reviewed. The review revealed that the physical, thermal, and biochemical treatments were reported to be effective in reducing antinutritional factors and improving protein solubility, emulsifying capacity, and foaming properties. Chickpea proteins were used in cereals and bakery products to meet consumer demand. Encapsulation of chickpea protein enhances nutrient stability, and its inclusion in gluten-free products has different effects on the glycemic index, antioxidant activity, and overall acceptability. These findings highlight chickpea's potential to improve the nutritional and functional aspects of food products while offering health benefits to consumers.

1. Introduction

Chickpea, with its scientific name *Cicer arietinum* and often colloquially called garbanzo bean, is a legume belonging to the Fabaceae family. The term "chickpea" finds its origins in the Latin word "cicer." It is widely cultivated across the world, with desi-type chickpeas accounting for 80% of production and Kabuli-type chickpeas accounting for the remaining 20% [1]. Desi-type chickpeas are distinguished by their pink flowers, the presence of anthocyanin pigmentation on stems, and a dense, colored seed coat [2]. In contrast, Kabuli-type chickpeas feature white flowers, lack anthocyanin pigmentation on stems, and possess a thin, white, or beige-colored seed coat with a smooth texture. India holds the distinction of being the world's largest chickpea producer, contributing approximately 70% of the overall global production [3]. In 2022, worldwide production of chickpeas was 15 million metric tons, with India producing 11 million metric tons, Turkey producing 630,000 metric tons, and Pakistan producing 493 metric tons [4].

Chickpea is abundant in protein, carbohydrates, and vitamins such as thiamine and niacin. It also contains essential minerals such as calcium, iron, phosphorus, magnesium, and potassium. Additionally, chickpeas provide both saturated and unsaturated fatty acids, including linoleic and oleic acid, along with dietary fibers, ash, polyphenols, and flavonoids [5]. The low cost, high protein content, and high protein digestibility of chickpeas make it a popular food source ingredient. Furthermore, chickpea protein can serve as a viable replacement for animal-derived protein (e.g., eggs and milk) in food products, which can increase the market demand for plant-based protein products and promote healthier and more sustainable food options [3]. The protein content of chickpeas varies between 20.90 and 25.27%, and it is composed of albumin (8.39 to 12.31%), globulin (53.14 to 60.29%), glutenin (3.12 to 6.89%), and prolamin (19.38 to 24.40%) [6]. Globulins are abundant in chickpea protein because they serve as crucial storage proteins in seeds, storing essential amino acids that support seed development and early seedling growth [7]. When seeds germinate, globulins break down into amino acids, providing readily available nutrients. Additionally, they play a role in maintaining seed structure [8]. Overall, globulins are vital in chickpeas for nutrient storage and early plant development. Chickpea also boasts a comprehensive and balanced variety of essential and nonessential amino acids. This includes lysine, leucine, methionine, phenylalanine, valine, tryptophan, histidine, arginine, cysteine, aspartic acid, glutamic acid, threonine, and glycine [9]. This comprehensive amino acid profile makes chickpea protein an appealing substitute for animal-based proteins such as eggs and milk, especially given the increasing demand for plant-derived protein products [10]. Nevertheless, it is important to note that chickpeas also contain certain antinutritional factors, such as tannins, phytic acid, and protease inhibitors. These components can influence the bioavailability of nutrients and may lead to digestive issues in certain individuals [11]. To counteract these adverse effects and boost the nutritional value of chickpeas, several pretreatment methods have been devised [6]. Various pretreatment methods are employed, such as physical techniques like biochemical and soaking, milling approaches like fermentation and germination, and thermal processes like extrusion and roasting, which are designed to remove or diminish antinutritional factors while enhancing the functional and nutritional attributes of chickpea protein [6].

Chickpea is acknowledged for its potential to provide health benefits, including its capacity to offer protection against chronic diseases such as heart disease, cancer, and type 2 diabetes [12]. Furthermore, it supports brain health, aids in weight management, and contributes to maintaining gut health and regular bowel movements [13]. Because of these advantages, chickpea finds extensive use in cereal-based food, bakery, and meat products, leading to improved nutritional value, rheological and sensory attributes, and enhanced functional attributes such as foaming, gelling, and emulsifying capabilities [14]. Additionally, it is employed in producing protein microencapsulates, which serve as carriers for nutrients [15]. Encapsulation of chickpea protein has been shown to improve the stability of folate, stability of emulsion oil droplets, physical integrity, and protection of carotenoids [16]. Incorporation of chickpea flour in gluten-free noodles, muffins, and sausages has been found to decrease glycemic index and starch digestibility, improve antioxidant activities and protein content, increase yield, texture, and global acceptability of sausages, and decrease hardness and browning index of muffins [17]. These findings indicate that chickpea holds promise as an element to elevate the nutritional and functional attributes of food products, potentially conferring health advantages to consumers [18]. The review evaluates the influence of these pretreatments on the nutritional, functional, and bioactive attributes of chickpea protein. It also discusses potential health benefits, such as enhanced digestibility and increased antioxidant activity. Furthermore, the review explores the implications of these pretreatments for the creation of novel food products, with the ultimate goal of optimizing the nutritional and functional attributes of chickpea-based products.

2. Nutritional and Chemical Composition of Chickpea

Chickpeas, scientifically known as *Cicer arietinum*, are a staple legume consumed worldwide for their remarkable nutritional value and diverse health benefits. These dry seeds offer a comprehensive composition of protein, carbohydrates, dietary fiber, vitamins, minerals, and bioactive compounds, earning them the moniker "poor man's meat" [19].

Carbohydrates play a pivotal role as the primary energy source in the human body, sustaining brain function, blood clot prevention, and diabetes management. Chickpeas encompass both available and unavailable carbohydrates, each contributing uniquely to human health [20]. Available carbohydrates, comprising monosaccharides and disaccharides, undergo enzymatic digestion in the small intestine [21]. Conversely, unavailable carbohydrates, including resistant starch, pectin, cellulose, and oligosaccharides, remain undigested, contributing to the dietary fiber content [22]. Notably, chickpeas contain several types of sugars, including glucose (0.05 to 0.06%), fructose (0.31 to 0.35%), maltose (0.33 to 0.35%), and sucrose (3.10 to 4.41%), each with distinct metabolic actions in the human body [11, 23–29]. Glucose, a monosaccharide, serves as a primary energy source and can be used immediately or stored as glycogen [30]. Fructose, another monosaccharide, is primarily metabolized in the liver and can be converted into glucose, glycogen, or fat [31]. Maltose, a disaccharide composed of two glucose molecules, is broken down into glucose for energy or storage [30]. Sucrose, a disaccharide comprising glucose and fructose, undergoes similar metabolic pathways, with glucose readily used for energy and fructose processed in the liver [32]. While chickpeas contain relatively small amounts of these sugars, they offer valuable nutrients such as fiber, protein, vitamins, and minerals, making them a nutritious food choice with sugars that follow the general metabolic processes in the body [21]. Oligosaccharides such as stachyose and ciceritol, although fostering gastrointestinal flatulence through bacterial fermentation, offer unique health advantages [33]. Additionally, chickpeas contain starch as the primary carbohydrate, consisting of amylopectin and amylose polymers, contributing to their energy-rich profile [34].

Protein content is a distinguishing feature of chickpeas, earning them recognition as a cost-effective protein source. Their protein content, ranging from 19.79% to 28.9%, is primarily composed of globulins (Table 1). While lacking in sulfur-containing amino acids such as cysteine and methionine, chickpeas abound in arginine and lysine. These amino acids contribute to protein synthesis and various metabolic processes [35]. Sodium dodecyl-sulfate polyacrylamide gel electrophoresis (SDS-PAGE) analysis reveals the qualitative distribution of albumin, globulin, prolamin, and salt-soluble protein levels in chickpeas [36]. Kabuli chickpeas exhibit higher protein digestibility (83.7 to 87.47%) compared to desi chickpeas (79.4 to 80.82%). Additionally, both chickpea varieties have higher digestibility rates than soy protein (70 to 72%) and green pea protein (72.65 to 75%). This highlights the nutritional advantages of chickpeas as a source of easily digestible plant-based protein [37–41].

Dietary fibers are complex carbohydrates found in plant-based foods, contributing to digestive health, blood sugar regulation, nutrient absorption, and cancer prevention. Chickpeas offer a substantial dietary fiber content, categorized into soluble and nonsoluble forms (Table 1). Soluble fibers are digested gradually, while nonsoluble fibers promote intestinal movement and beneficial gut bacteria proliferation through fermentation. The desi variety of chickpeas displays higher insoluble fiber content due to its thicker seed coat, while both desi and Kabuli types exhibit similar soluble fiber content. These fibers, including hemicelluloses and oligosaccharides, contribute to a balanced diet, fostering a healthy gut environment. The soluble and insoluble fibers in chickpeas contribute to improved digestive health by preventing constipation and promoting regular bowel movements [21]. Moreover, the soluble fiber may help stabilize blood sugar levels and reduce LDL cholesterol, enhancing cardiovascular health [33]. Chickpeas' high fiber content also aids in weight management by promoting a feeling of fullness and controlling appetite [36]. Additionally, their fiber content can support a healthy gut microbiota, potentially strengthening the immune system and reducing the risk of colon cancer. Incorporating chickpeas into the diet, along with a variety of other fiber-rich foods, can contribute to these positive health outcomes [11, 23–29].

Amino acids are organic compounds that are the building blocks of proteins. They are essential to the structure and function of all living organisms. Amino acids are made up of an amino group (-NH2), a carboxyl group (-COOH), and a side chain (R group) that is unique to each amino acid [42]. The amino acid composition of chickpeas contributes to their superior protein quality. While exhibiting slight variations in amino acid content, chickpeas offer a well-rounded amino acid profile as shown in Table 1. Essential amino acids such as leucine, lysine, methionine, threonine, phenylalanine, and valine are present, although cysteine and methionine contents are limited. Nonessential amino acids such as aspartic acid, glutamic acid, serine, glycine, alanine, tyrosine, and proline contribute to various metabolic pathways, neurotransmitter synthesis, and overall bodily functioning. The abundant presence of these amino acids further enhances chickpeas' nutritional value [43].

Lipids, a diverse group of biomolecules, are vital for energy storage, vitamin absorption, and nerve functioning. Chickpeas contain approximately 2.70 to 6.48% crude fat content, comprising saturated and unsaturated fatty acids. These lipids include essential fatty acids such as linoleic acid (42.25 to 62.65%) and oleic acid (18.44 to 27.7%), contributing to positive effects on cardiovascular health, including the reduction of LDL cholesterol levels and potential anti-inflammatory benefits [44]. It is also essential for maintaining the structure and function of cell membranes [45]. Additionally, chickpeas contain linoleic acid, an essential polyunsaturated fatty acid belonging to the omega-6 family [46]. Linoleic acid plays a role in cell membrane structure but should be consumed in balance with omega-3 fatty acids to avoid promoting excessive inflammation [47].

Chickpeas are also rich in minerals, essential for various physiological functions. Potassium, phosphorus, calcium, sodium, magnesium, iron, copper, zinc, and manganese are abundant in chickpeas, supporting bone health, nerve function, immune system, and overall well-being [48]. Selenium, a trace element present in chickpeas, holds nutritional significance for human health [49]. Vitamins, another crucial component of chickpeas, encompass vitamin C, riboflavin, thiamine, and retinol. These vitamins contribute to immune function, energy production, support metabolic processes, brain function, nerve function, improve skin and eye health, support DNA repair, and improve cholesterol metabolism [48]. The presence of carotenoids in chickpeas, including beta-carotene, lutein, and zeaxanthin, serves as antioxidants, protecting against chronic diseases, supporting eye and skin health, boosting the immune system, and potentially reducing the risk of certain cancers [50]. Lastly, chickpeas contain bioactive compounds such as isoflavones, including formononetin and biochanin A, which help to regulate hormonal balance, improve bone health by increasing bone mineral density, improve heart health by lowering LDL cholesterol levels, and enhance blood vessel function [51]. Additionally, their antioxidant properties may contribute to reducing the risk of chronic diseases and certain types of cancer [52]. These compounds, along with other nutrients such as fiber, protein, vitamins, and minerals, make chickpeas as a nutritious addition to a well-balanced diet that can positively impact overall human health [11].

3. Pretreatments on Chickpea

Chickpeas undergo various pretreatments to enhance their palatability, nutritional value, and digestibility. These methods encompass physical (milling and soaking), biochemical (germination and fermentation), and thermal (roasting and extrusion) techniques. Chickpeas have a global presence, featuring prominently in Middle Eastern, Mediterranean, and Southeast Asian cuisines. In the Middle East, chickpeas are blended into creamy hummus with tahini and spices. Mediterranean cuisine highlights chickpeas in crispy falafel, while Southeast Asia uses soaked chickpeas in curries. Globally, chickpeas feature in salads, soups, and vegetarian dishes, showcasing their adaptability across diverse culinary

Table 1: Nutritional and chemical composition of chickpea.

Type	Constituents	Concentration		Reference
		Desi chickpea (%)	Kabuli chickpea (%)	
Carbohydrates	*Monosaccharides*			[11, 23–29]
	Fructose	—	0.31–0.35	
	Galactose	—	0.010–0.015	
	Glucose	—	0.05–0.06	
	Disaccharides			
	Maltose	—	0.33–0.35	
	Sucrose	1.56–2.88	3.10–4.41	
	Oligosaccharides			
	Ciceritol	1.93–4.00	1.90–4.10	
	Stachyose	1.25–1.98	1.25–1.98	
	Raffinose	0.46–0.77	0.46–0.77	
	Polysaccharides			
	Starch	33.10–50.60	38.20–51.60	
Protein		19.79–23.68	21.26–28.9	[11, 23–29]
Fiber	Soluble	3.70–13	1.17–4.96	[11, 23–29]
	Insoluble	9.60–18.21	11.22–19.60	
Ash		2.38–3.22	2.37–3.54	[11, 23–29]
Amino acids	*Essential amino acids*			[11, 23–29]
	Arginine	8.00–13.60	8.84–13.70	
	Histidine	1.70–3.27	1.70–3.00	
	Isoleucine	—	—	
	Leucine	8.20–14.24	2.48–8.20	
	Lysine	4.90–7.25	5.20–7.60	
	Methionine	1.10–1.70	0.80–1.70	
	Phenylalanine	4.50–5.90	4.50–5.90	
	Threonine	1.40–4.02	1.40–4.02	
	Tryptophan	0.70–1.11	0.80–1.10	
	Valine	2.70–4.71	2.80–4.70	
	Nonessential amino acids			
	Alanine	3.60–5.20	3.52–4.70	
	Aspartic acid	10.73–15.90	9.9–12.90	
	Cystine	1.10–2.98	0.40–2.0	
	Glutamic acid	13.40–19	13.10–17.50	
	Glycine	3.30–4.20	3.20–4.50	
	Proline	4.00–6.00	2.95–6.50	
	Serine	3.20–6.90	3.70–7.33	
	Tyrosine	1.40–3.10	2.20–6.93	
Minerals	Sodium (mg/100 g)	22.90–27.35	21.07–28.12	[11, 23–29]
	Potassium (mg/100 g)	1026.80–1490.00	814.00–1581.00	
	Phosphorus (mg/100 g)	275.22–520.28	230.00–830.80	
	Calcium (mg/100 g)	112.00–229.60	115.14–226.47	
	Iron (mg/100 g)	4.50–7.00	4.20–7.65	
	Copper (mg/100 g)	0.40–1.40	0.60–1.42	
	Zinc (mg/100 g)	2.70–5.15	3.60–5.60	
	Manganese (mg/100 g)	2.75–4.10	2.20–4.80	
	Magnesium (mg/100 g)	142.70–188.60	153.00–213.80	

Table 1: Continued.

Type	Constituents	Concentration		Reference
		Desi chickpea (%)	Kabuli chickpea (%)	
Lipid	*Saturated fatty acid*			[11, 23–29]
	Lauric acid (C12, 0) (% total fatty acid)	0.00–0.10	—	
	Myristic acid (C14, 0) (% total fatty acid)	0.17–0.32	0.19–0.26	
	Palmitic acid (C16, 0) (% total fatty acid)	8.56–11.0	8.52–10.3	
	Stearic acid (C18, 0) (% total fatty acid)	1.04–1.60	1.21–1.68	
	Arachidic acid (C20, 0) (% total fatty acid)	0.45–0.74	0.59–0.76	
	Behenic acid (C22, 0) (% total fatty acid)	0.30–0.42	0.29–0.48	
	Lignoceric acid (C24, 0) (% total fatty acid)	—	0.00–0.29	
	Unsaturated fatty acid			
	Palmitoleic acid (C16, 1) (% total fatty acid)	0.23–0.30	0.27–0.34	
	Oleic acid (C18, 1) (% total fatty acid)	18.44–28.5	27.7–42.6	
	Linoleic acid (C18, 2) (% total fatty acid)	53.10–62.65	42.25–56.59	
	Gadoleic acid (C20, 1) (% total fatty acid)	0.41–0.59	0.48–0.70	
	Eicosadienoic acid (C20, 2) (% total fatty acid)	0.08–0.15	0.00–0.09	
	Erucic acid (C22, 1) (% total fatty acid)	0.00–0.21	0.00–0.16	
Vitamins	Retinol (A) (μg/100 g)	—	—	[11, 23–29]
	Vitamin C (mg/100 g)	2.15–6.0	2.17–5.8	
	Thiamin (B1) (mg/100 g)	0.028–0.40	0.026–0.40	
	Riboflavin (B2) (mg/100 g)	0.15–0.30	0.10–0.25	
	Niacin (B3) (mg/100 g)	1.60–2.90	1.80–2.10	
	Folic acid (mg/100 g)	0.15–0.30	0.15–0.32	

traditions. In India, chickpeas are primarily consumed as "dhal" or flour, with "chana dhal" produced by dehulling and splitting the cotyledons and besan (chickpea flour) being essential in traditional Indian dishes such as boondi, dhokla, pakora, bhujia, and sweets, used as batter, paste, or dough. These processes also help eliminate antinutritional factors, reducing processing time and making chickpeas more appealing and nutritious [50].

3.1. Physical Treatments

3.1.1. Soaking. Soaking also referred to as steeping is a granulation hydration technique that facilitates the absorption of water into the cells, thereby increasing the moisture content. It serves as a vital initial stage in numerous processes, including germination, boiling, extraction, and fermentation [53]. The process of soaking also causes a leaching effect of several soluble compounds, including phytic acid, tannins, and oligosaccharides. Additionally, it can soften the grain structure, resulting in a reduction in the required cooking time [54]. This phenomenon is attributed to the activation of cell wall enzymes that enhance by reducing the rate of rhamnogalacturonan-I polymerization and increasing the solubility of polygalacturonase and galactan, and it enhances the solubility of polysaccharides. As a result, there is a reduction in cooking time [55]. When chickpea seeds are soaked overnight, there is a considerable decrease in tannin concentration by 53%, along with a reduction in carbohydrate content by 20-21% [24]. Studies have indicated that the reduction in the overall concentration of phenolic compounds decreases with an increase in the duration of hydration due to the initial removal of phenolic content in the soaking water [53]. Moreover, the absorption of water during the soaking process can improve the transmission of cooking heat, leading to enhanced deactivation of several antinutritional agents, including nondigestible oligosaccharides, lectins, protease inhibitors, phytase, alkaloids, and saponins [56]. Furthermore, grain hydration plays a vital role in providing the required water activity for microorganisms during fermentation. Several mathematical models have been devised to examine the hydration process of grains during soaking. These models help assess time-dependent moisture content, study equilibrium moisture content, lag phase time and hydration rate, and analyze moisture behavior, including the duration of the descending sigmoidal and concave shape [57]. Various mathematical models, including the Peleg [58], Weibull [59], Nicoline-Jorge [24], and Khazaei models [60], are commonly used to study hydration kinetics. Hydration involves a mass transfer, where the difference in water activity acts as the driving force for moisture absorption by the grains during the process, which is essentially a mass transfer phenomenon. The mechanism of hydration includes surface absorption, capillary action, and interstitial absorption [61]. Initially, water is absorbed by the grain's outer layers, progressing deeper into the grain structure through capillary channels and eventually occupying spaces between various constituents within the grain. Several conditions influence the process of hydration [62]. A crucial factor is the water activity gradient, where a higher gradient results in more rapid and extensive hydration. The contact time, temperature, and relative humidity also play significant roles. Control over these conditions is vital to achieve the desired moisture content in the grains without compromising their quality [63]. The implications of hydration for the quality of grains during processing are substantial. Proper hydration can enhance the texture, reduce cooking time, and influence the flavor profile of grains, making them more palatable [62]. However, it is essential to avoid overhydration, which can result in an undesirable texture and potential issues with shelf life. Striking the right balance between moisture content and structural integrity is critical, making hydration a pivotal step in the food processing industry [61]. In most legume seeds, due to the impermeable seed coat, water absorption mainly occurs through the hilum, and it subsequently spreads throughout the space between the seed coat and the cotyledon of the seed [24]. The process ultimately leads to the endogenous hydration of the seed coat, which confers the ability to absorb water efficiently. Consequently, hydration takes place via both the hilum and the process of diffusion through the seed coat. The hydration process of the grain persists until optimal moisture equilibrium is achieved. The enhanced water permeability of the seed coat contributes to the increase in the initial moisture content. The hydration behavior of the grain is significantly influenced by its initial moisture content [64].

Soaking is a common preparatory step for chickpeas, and it impacts the protein structure at various levels: primary, secondary, and tertiary. At the primary level, which involves the linear sequence of amino acids, soaking does not cause significant changes. The core amino acid sequence remains unchanged [65]. However, the effects of soaking become more noticeable at the secondary and tertiary structural levels. The secondary structure involves folding patterns held by hydrogen bonds. Soaking disrupts these bonds, leading to the partial or complete unfolding of structures such as α-helices and β-sheets. These well-defined patterns become less stable, potentially transforming into random coil structures [66]. Moving to the tertiary structure, soaking significantly affects the protein's three-dimensional arrangement, influenced by various interactions like hydrogen bonds, disulfide bonds, hydrophobic interactions, and electrostatic interactions. Water molecules penetrate the protein matrix during soaking, undermining hydrophobic interactions crucial for maintaining the compact, globular tertiary shape [67]. This disruption can trigger partial or complete unfolding, altering the protein's three-dimensional shape and potentially exposing hidden hydrophobic regions. The extent of soaking's impact on protein structure depends on factors such as the protein's inherent stability and soaking conditions. More stable proteins are more resilient to soaking, preserving their structure better. Less stable proteins are more susceptible to unfolding and alterations caused by soaking [68]. Chickpea protein, specifically globulins, is stable and retains its structure during soaking, preserving its qualities [17]. In contrast, whey protein and wheat proteins like gliadins are less stable and can undergo alterations when soaked, affecting the final product's quality [67].

Soaking chickpeas serves as the initial step to reduce any undesirable odors, flavors, and aromas [69]. As chickpeas absorb water during soaking, it helps remove some of the compounds responsible for the earthy and slightly musty odor associated with raw chickpeas [70]. This results in a milder, less bitter flavor with cleaner, less pungent aromas [71]. Additionally, soaking contributes to a milder and less "beany" flavor, making chickpeas more versatile in various culinary applications. Soaked chickpeas are often considered more palatable and are an essential precursor to various chickpea-based dishes [72].

Chickpea protein, when subjected to soaking pretreatment, offers a range of health benefits. This process enhances the digestibility of chickpeas by breaking down complex carbohydrates and reducing antinutrients like phytic acid, ultimately improving nutrient absorption [73]. Consuming chickpea protein after this pretreatment can contribute to balanced blood sugar levels due to its lower glycemic index. Additionally, the reduction in antinutrient content supports heart health by lowering cholesterol levels. The protein content in chickpeas, coupled with their fiber, aids in muscle building and repair while promoting a feeling of fullness, contributing to weight management [74]. Moreover, the soluble and insoluble fiber in chickpeas supports gut health by facilitating regular bowel movements and fostering a diverse microbiota [72].

The study conducted by Kaur and Prasad [75] found that after soaking (8 h, 35°C), the Kabuli variety of chickpeas exhibited increases in protein content by 1.59%, crude oil content by 18.81%, and protein digestibility by 12.81%. This treatment on chickpeas also reduced antinutritional factors such as tannin and phytate by 21.68% and 22.72%. The ash and carbohydrate contents in the chickpea were also reduced by 10.29 and 1.49%.

In the research of Sofi et al. [76], it has been observed that the protein obtained from Kabuli variant of chickpea has diverse effects on its chemical composition after soaking (12 h, 27°C). The moisture, fat, and fiber contents of chickpea protein have increased by 4.81%, 2.35%, and 30.94%, respectively, and the increase in moisture, fat, and fiber contents of chickpea protein after milling is primarily due to the mechanical forces applied during the milling process, which can release moisture and fat and make the fiber more accessible for measurement. The mineral content decreased, such as zinc, iron, and calcium, by 0.78%, 3.97%, and 2.26%, respectively.

In the research of Olika et al. [77], the study revealed that the soaking (24 h, 30°C) Kabuli chickpea experienced a reduction in antinutritional factors, with phytate and tannin by 14.21% and 49.79%, respectively. Additionally, functional properties such as water and oil-holding capacity increased by 1.35% and 1.05%, respectively.

3.1.2. Milling. Milling is a process that involves reducing the size of larger particles to smaller ones. When applied to desi chickpea, this process entails separating the seed coat followed by splitting the cotyledons to create chickpea splits, commonly known as "chana dal." These chickpea splits are popularly used in traditional Indian cuisine [78]. The milling procedure consists of several steps: dehulling refers to the removal of the outer seed coat of a chickpea. The seed coat is primarily composed of lignin, cellulose, minerals, and polyphenols and serves to protect the seed from physical damage, pests, and premature germination [79]. Removing the seed coat has various benefits, including increased protein digestibility, nutritional value, palatability, and reduced levels of antinutritional factors and insoluble fibers [80]. In India, pulses are predominantly consumed as flour or "dhal," accounting for approximately 80% of total pulse consumption. After the dehulling process, the chickpeas are split into two cotyledons to form chana dhal. Dehulling and splitting can be achieved through two methods: dry milling and wet milling [81]. The process of milling or grinding chickpeas leads to the release of a slightly nutty and flour-like odor [82]. This mechanical breakdown of the chickpea structure results in a more concentrated, nutty, and mildly savory flavor compared to whole chickpeas. Changes in flavor may occur due to Maillard reactions, and texture can be impacted, ranging from smoother textures with fine milling to more granular textures with coarse milling [83]. The aroma of milled chickpea protein is typically subtle, carrying a mild nuttiness that can be utilized in various culinary applications, including flour for baking and protein powders [84].

Besan, also known as chickpea flour, is a common ingredient in traditional Indian dishes such as boondi, dhokla, pakora, bhujia, and sweetmeats, often used as a batter, paste, or dough. Boondi, a deep-fried snack, is made by immersing chickpea flour droplets in hot oil. Chickpea flour is primarily sourced from dehulled chickpea seeds [85]. The nutritional composition of whole grain and milled grain significantly varies due to the exclusion of an outer layer that contains nutrients such as polyphenols and dietary fiber and antinutritional factors such as phytic acid and trypsin inhibitors. While milling improves the digestibility of carbohydrates and protein, it also leads to a decrease in antioxidant properties due to the removal of polyphenolic compounds present in the seed coat [86].

After undergoing milling pretreatment, chickpea protein emerges as a nutritional powerhouse, offering a myriad of health benefits. The milling process enhances the bioavailability of essential amino acids, promoting optimal muscle development and repair [87]. Additionally, the milling pretreatment facilitates the breakdown of antinutritional factors, enhancing digestibility and absorption of nutrients. The resulting protein is rich in fiber, aiding in digestive health and promoting a feeling of fullness, which can be beneficial for weight management [88]. Moreover, chickpea protein is a low-calorie option that supports cardiovascular health by helping to regulate cholesterol levels. Packed with vitamins and minerals, including iron, magnesium, and zinc, chickpea protein contributes to overall well-being, immune function, and energy metabolism [12].

The research findings of Ravi and Harte [89] indicate that wet milling of chickpeas results in a 2–4% higher yield of dhal compared to dry milling. Gel electrophoresis analysis showed no significant differences in the protein profiles of chickpeas between wet and dry milling methods. Both methods exhibited 15 protein bands in both phosphate and SDS buffers. Furthermore, the study observed variations in the nutritional composition between Kabuli and desi chickpeas. Kabuli chickpeas displayed higher fat, ash, and protein contents compared to desi chickpeas. Specifically, the values were 5.3% fat, 3.5% ash, and 24.9% protein for Kabuli, while desi chickpeas had 4.3% fat, 2.2% ash, and 22.6% protein.

A study conducted by Espinosa-Ramírez and Serna-Saldívar [90] shows that when chickpea protein underwent milling treatment, the protein content increased by 9.3%, but the overall protein yield decreased by 48.93%. Furthermore, functional attributes such as solubility, foaming capacity, and oil holding capacity increased by 1.78%, 5.12%, and 37.33%, respectively. On the other hand, water holding capacity and emulsion activity decreased by 43.39% and 1.30%.

In summary, soaking and milling are crucial steps in chickpea processing, impacting their quality and functionality. Soaking hydrates chickpeas reduces cooking time and deactivates antinutritional substances. The effects on nutrition depend on soaking duration. Milling, including dehulling and splitting, improves protein digestibility, taste, and nutritional value while reducing antinutrients and insoluble fibers. However, it may remove polyphenols, affecting antioxidant properties. These treatments are essential for optimizing chickpeas' attributes for various scientific and culinary applications, such as Besan in Indian cuisine, but should be tailored to specific goals.

3.2. Biochemical Treatments

3.2.1. Germination. The process of soaking grains in water and maintaining them in a humid environment until germination is known as sprouting. Sprouting can improve the nutritional quality of grains by enhancing the digestibility of protein and starch, increasing vitamin content, and improving mineral bioavailability [91]. Moreover, this treatment has been found to diminish antinutritional compounds, such as phytic acid, tannins, and alpha-galactose-oligosaccharides, including stachyose and raffinose. According to the American Association of Cereal Chemists (AACC), whole grains are those that have undergone the germination process, contain all parts of the kernel, including the bran, germ, and endosperm, have sprouts that are not longer than the kernels, and have retained their nutritional value without any damage [92]. The process of germinating grains involves soaking, where the dormant state of the seeds is disrupted due to their ability to absorb water. This process involves three distinct stages, namely, the imbibition phase, the activation of biochemical processes, and the development of a radicle [93]. The imbibition phase involves the initial absorption of water by the dormant seed, causing it to swell and rehydrate [94]. This critical step reactivates the seed's metabolic activity, breaking the dormancy and softening the seed coat to allow for further growth. The second phase involves the activation of biochemical processes within the seed [95]. Enzymes become active, facilitating the conversion of stored reserves into sugars and other nutrients that serve as an energy source for the developing embryo. This phase is pivotal in providing the necessary resources for the growing plant [96]. Finally, the third phase is the development of the radicle, the embryonic root of the plant. As the embryo grows, the radicle elongates and emerges from the seed, anchoring the plant into the soil and allowing it to access essential water and nutrients [97].

Subsequently, the shoot emerges, and the plant continues its growth and development into a mature plant, marking the successful completion of the germination process [98]. Among the various factors affecting the nutritional quality of sprouted chickpeas, the duration of germination has been found to have the greatest impact, while light or darkness does not play a significant role [99]. Chickpeas contain oligosaccharides such as stachyose and raffinose, which are not readily digestible due to insufficient alpha-galactosidase enzymes in the human digestive system. Germination triggers the production of enzymes that break down complex carbohydrates, resulting in a significant reduction in the number of alpha-galactose-oligosaccharides, primarily raffinose and stachyose [92]. During germination, stored proteins are broken down into amino acids, which serve as an energy source for further growth and development. Studies indicate that the protein solubility of the Arerti and Natoli varieties of chickpea protein increases by 6.67% and 2.79% after 24 h of germination, compared to non-germinated seeds [100].

Germination is a complex process that entails profound changes in chickpea protein structure. Germination marks the transformation of a seed into a growing plant, involving enzymatic activities to metabolize stored nutrients, including proteins, and supporting seedling development [101]. Among the significant shifts in protein structure during germination is the degradation of storage proteins. Chickpeas encompass globulins, particularly 11S and 7S globulins, and are rich in essential amino acids, serving as crucial nutrient reserves for the seed. During germination, proteases become activated, initiating hydrolysis of these storage proteins into smaller peptides and free amino acids and fueling seedling growth [102]. These liberated amino acids are transported to different parts of the seedling for new protein synthesis to sustain development. Throughout germination, modifications in secondary and tertiary protein structures transpire. Water molecules and enzymes interacting with proteins incite conformational changes, where hydrogen bond disruptions unravel secondary structure elements, such as alpha-helices and beta-sheets [103]. Tertiary structures, fortified by hydrophobic interactions, also feel the impact of germination. As water infiltrates seeds and interacts with proteins, hydrophobic regions might be exposed, inducing partial or complete unfolding of protein molecules [104].

Germination offers a natural way to enhance the sensory qualities of chickpea protein. The odor of germinated chickpea protein can develop earthy or grassy notes, distinct from the raw chickpea odor. In terms of aroma, germinated chickpeas may exhibit a more complex profile with nutty or sweet undertones [105]. The flavor of germinated chickpeas is typically milder and less astringent, often featuring a slight nuttiness or sweetness, while bitterness may decrease [70]. Germinated chickpea protein can be a desirable ingredient in salads, snacks, and other health-focused products [105].

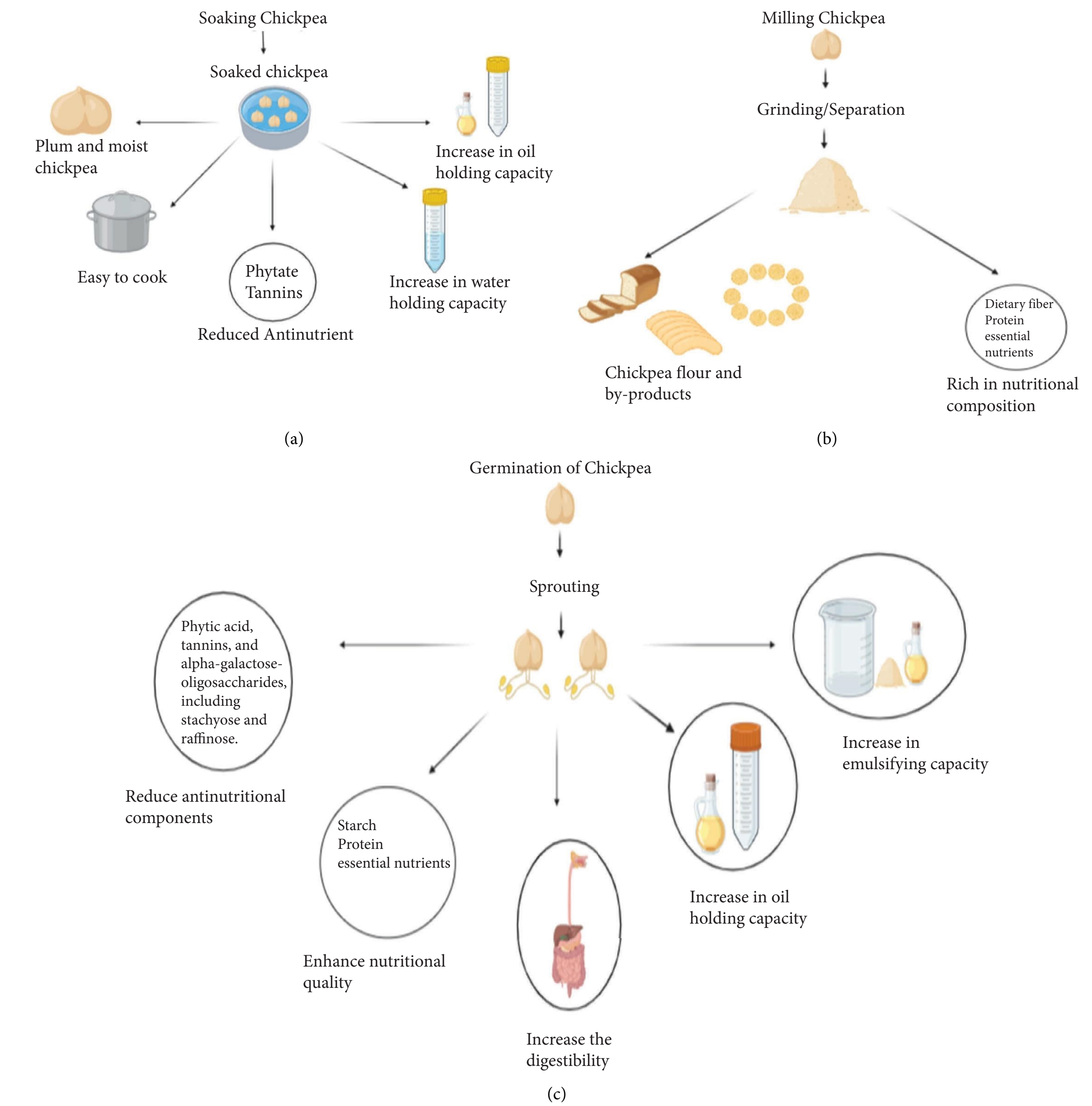
Chickpea protein, derived after germination pretreatment, offers distinct health benefits compared to conventional soaking methods. The germination process activates enzymes, increasing the bioavailability of nutrients, notably proteins with a superior amino acid profile [106]. Enhanced protein digestibility and improved fiber content contribute to better nutrient absorption and digestive health. Additionally, germination reduces antinutrients like phytic acid, potentially boosting the absorption of essential minerals [107]. The antioxidant levels are higher in germinated chickpeas, providing increased protection against oxidative stress and supporting overall health. Furthermore, the process may lead to elevated vitamin content, including vitamins C and B. Germinated chickpea protein represents a favorable option for those seeking allergen reduction and improved blood sugar regulation, making it a valuable addition to a health-conscious diet [11].

The research findings of Kaur et al. [108] demonstrate that chickpea protein digestibility increased by 6.25% after 48 h of germination. Furthermore, germinated seeds (24 h) showed an increase in protein content by 4.08% in Arerti and 4.36% in Natoli compared to their native chickpea protein.

The study shows that in 24 h, germinated chickpeas exhibited a reduction in protein, fat, and ash content by 49.79% and 15.72% in Arerti, and 45.33% and 30.25% in Natoli, respectively. The water, oil holding, and foaming capacity increased by 21.24%, 16.39%, and 25% in Arerti and 13.88%, 22.16%, and 39.5% in Natoli as compared to native chickpea protein [109, 110].

According to the study conducted by Ferreira et al. [100], germination resulted in a substantial increase in the total phenolic content of the desi and Kabuli variety of chickpea protein. Specifically, the total phenolic content showed an increase ranging from 16.2% to 51.6% for desi and 39.1% to 76.6% for Kabuli chickpeas.

3.2.2. Fermentation. Fermentation, a traditional method for preserving food, provides several advantages, including increased digestibility, elevated nutritional value, and enhanced flavor, while simultaneously decreasing antinutritional factors [111]. There are two main methods of food fermentation: submerged fermentation and solid-state fermentation. Submerged fermentation uses a high volume of water, leading to higher product yields, lower waste management costs, and superior product characteristics. Conversely, solid-state fermentation is carried out in the absence or presence of minimal free water, facilitating concentrated substrates for the microorganisms and efficient waste management [112]. Solid-state fermentation is the preferred method for fermenting foods and dietary proteins. The production of organic acids during fermentation leads to an acidic environment, which reduces the potential for harmful microorganism proliferation [113]. Additionally, vitamin concentrations, specifically those of ascorbic acid, thiamine, niacin, and riboflavin, increase significantly during fermentation, and protein digestion is improved (Figure 1(d)) [114]. Studies indicate that fermentation reduces the chymotrypsin and trypsin activity and also diminishes the concentration of phytates [5]. Legumes and cereals are the most commonly processed foods for solid-state fermentation, resulting in products with increased nutritive value and



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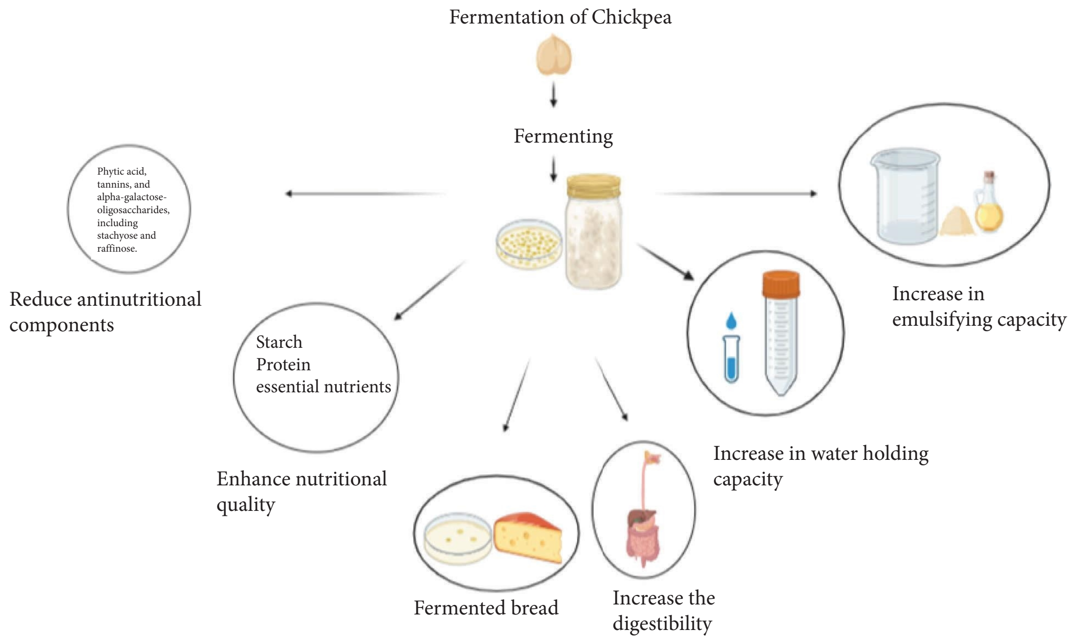
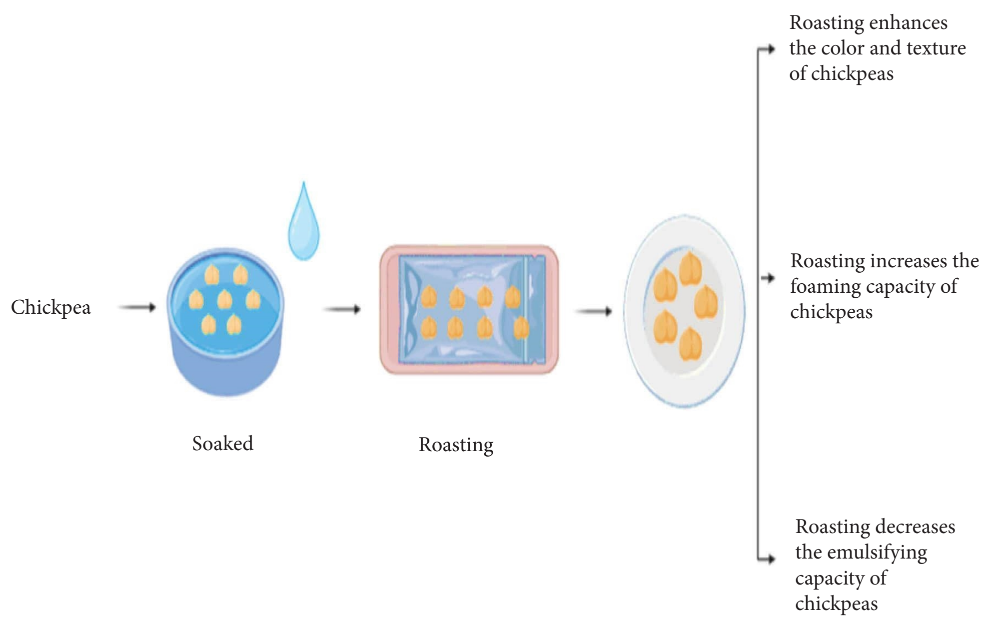


(d)



(e)

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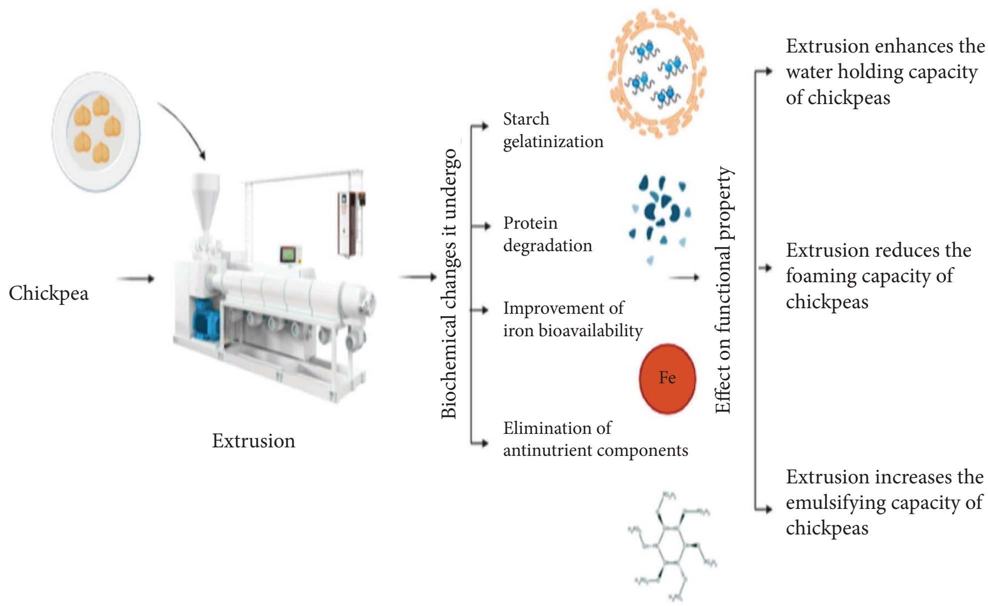

(f)

Figure 1: Soaking (a), milling (b), germination (c), fermentation (d), roasting (e), and extrusion (f) treatment of chickpea seed.

improved flavor [115]. During fermentation, the alpha-glucosidase enzyme is activated, which hydrolyzes raffinose, stachyose, verbascose, and other oligosaccharides into digestible sugars [116]. A similar outcome was observed during the 45-h fermentation of urad beans [117]. Tempeh, a fermented food made from soybeans, is a typical example of a food item manufactured through fermentation. However, efforts have been made to optimize the process parameters to use chickpeas as a substrate. Khaman dhokla, a traditional Indian culinary item, is made by fermenting and dehulling bengal gram flour overnight, followed by steaming to create a soft, spongy-textured cake with a spicy flavor [118]. Lactic acid bacteria play a crucial role in producing a sour taste and pleasant flavor during chickpea fermentation [119]. Some Mediterranean countries use fermented chickpeas as a leavening agent for making traditional bread and rusks [120]. In Greece, chickpeas that have been coarsely mashed and fermented for about 18 h are utilized to produce chickpea bread, also known as "Eftazymo" (a substance that is "fermented on its own"). Lactic acid bacteria dominate the microflora in chickpea fermentation, leading to a decrease in yeast and mold populations in chickpea sourdough. In submerged fermentation of chickpea flour, *Clostridium perfringens CP8*, *Bacillus cereus*, *Bacillus licheniformis*, and *Bacillus thuringiensis* species become predominant in the microflora [121]. *Rhizopus oligosporus* spore suspensions can be utilized for the solid-state fermentation of chickpeas. The resulting fermented chickpea flour displays increased protein content and improved in-vitro protein digestibility compared to raw chickpea flour. Additionally, the fermentation process leads to a reduction in phytic acid and tannin content [122]. Moreover, solid-state fermentation of dehusked chickpea cotyledons using *Rhizopus oligosporus* enhances their antioxidant properties and phenolic content [123]. Fermentation time plays a crucial role in the extent of protein degradation and the formation of peptides and amino acids. Shorter fermentation times tend to preserve the native protein characteristics, while longer durations can lead to increased proteolysis and structural changes, affecting the texture and flavor of the final product [124]. *Clostridium perfringens* CP8, *Bacillus cereus*, and *Bacillus licheniformis* are all known for their proteolytic capabilities, potentially breaking down chickpea protein into smaller compounds. The resulting impact on flavor and aroma can range from pungent and savory notes to complexity and umami [125].

During fermentation, notable alterations take place in the structure of chickpea proteins. Fermentation is a microbial process wherein microorganisms, like bacteria or yeast, convert organic compounds under controlled conditions [126]. These changes in protein structure contribute to the development of unique flavors, textures, and nutritional properties in fermented chickpea products. In terms of the primary structure, fermentation typically does not introduce substantial modifications to the amino acid sequence of chickpea proteins [127]. The primary structure remains largely unchanged during the fermentation process. However, enzymatic activity from microorganisms may result in the breakdown of proteins into smaller peptides and free amino acids. This proteolytic activity can lead to the release of savory and umami flavor compounds, contributing to the overall taste profile of the fermented product [128]. In terms of the secondary structure, fermentation can induce changes due to the action of microbial enzymes and the acidic or alkaline conditions created during fermentation. The interaction between microbial enzymes and chickpea proteins can disrupt the hydrogen bonds that stabilize the secondary structure elements, such as α-helices and β-sheets [129]. This disruption can lead to the unfolding or rearrangement of the secondary structure, resulting in changes in protein conformation. The tertiary structure of chickpea proteins can also be affected during fermentation [130]. The changes in pH and the production of metabolites by microorganisms can influence the hydrophobic interactions, disulfide bonds, and other noncovalent interactions that maintain the folded structure of proteins [131]. As a result, the tertiary structure may undergo partial or complete unfolding, exposing buried hydrophobic regions and altering the overall shape of the protein molecules. The specific changes in protein structure during fermentation depend on various factors, including the type of microorganisms involved, the fermentation conditions (such as temperature, pH, and duration), and the composition of the chickpea substrate [132]. Different microorganisms produce specific enzymes that target different protein structures, leading to diverse modifications [132].

Fermentation has a multifaceted impact on chickpea proteins, encompassing changes in odor, aroma, flavor, and sensory attributes. Through fermentation, chickpea proteins can transform odor, often leading to a reduction in any raw, beany aroma and resulting in a milder and more pleasant aroma profile [127]. Aroma is also significantly influenced, as fermentation introduces new aromatic compounds, enhancing the overall aromatic complexity of chickpea-based products. When it comes to flavor, fermentation can mitigate bitterness and enhance umami or pungent flavor [133]. Fermented chickpea protein is used in a variety of culinary applications, such as condiments, sauces, and plant-based dairy alternatives [134].

Chickpea protein, following fermentation pretreatment, offers unique health benefits distinct from traditional soaking and germination methods. Fermentation involves the action of beneficial microorganisms on chickpeas, transforming their nutritional composition. The health benefits of fermented chickpea protein include improved digestibility due to the breakdown of complex compounds, making nutrients more bioavailable [115]. Fermentation can also enhance the production of bioactive compounds, such as peptides and organic acids, contributing to gut health and potentially exerting antiinflammatory effects [135]. Unlike soaking and germination, fermentation promotes the growth of probiotics, beneficial bacteria that support a healthy gut microbiome, aiding in digestion and nutrient absorption [136]. Additionally, fermented chickpea protein may have increased levels of certain vitamins and antioxidants, providing potential immune system support and reducing oxidative stress [137].

The research demonstrated that conducting solid-state fermentation of chickpea flour using *Cordyceps militaris* SN-18 for a period of 4 days at a temperature of 25°C results in a significant increase of 19.43% in protein content, as well as an improvement in emulsifying ability and stability of protein, which increased by 73.79% and 12.30%, respectively [138].

In addition, the utilization of *Pediococcus pentosaceus* strain VMCU76F in solid-state fermentation of chickpea flour for 24 and 72 h at 37°C resulted in a pH reduction from 6.6 to 4.2 within 24 h. Furthermore, after 72 h of fermentation, the total phenolic content and water-holding capacity of protein increased by 119% and 67%, respectively. Additionally, there was a significant reduction of 17%, 99.1%, and 88.3% in phytic acid, stachyose, and raffinose in a protein, respectively, after 72 h of fermentation [139].

In summary, germination and fermentation offer promising ways to enhance chickpea protein's nutritional value and functional properties. Germination improves digestibility, reduces antinutrients, and boosts beneficial compounds. It also alters fat, ash, and fiber content and enhances water-holding and emulsion capacity [140]. Fermentation enhances digestibility, increases bioactive compounds, and reduces antinutrients such as phytic acid and tannins [141]. Solid-state fermentation improves protein content, emulsifying ability, and stability [142]. These treatments optimize chickpea protein, making it a valuable ingredient for nutritious and flavorful food products.

3.3. Thermal Treatments

3.3.1. Roasting. The processing of chickpeas commonly involves the utilization of the roasting method, whereby the seeds are exposed to high temperatures for a short duration. Roasted chickpeas are a popular snack food in India and can be consumed with or without hulls. The taste of roasted chickpeas can be enriched by applying jaggery coatings or roasting them with salt [143]. Roasting improves the color and texture of the food, making it more appealing. Roasted chickpeas are also utilized in the preparation of sattu powders, drinks, and desserts [144]. In Turkish, Iranian, and Afghan cultures, they are commonly referred to as leblebi. Before roasting, chickpeas are soaked and tempered to enhance their texture. Soaking leads to swelling and softening, while roasting creates a crispy texture. During roasting, high temperatures cause the moisture inside chickpeas to convert into superheated vapors, increasing pressure and leading to sputtering of the grain [145]. Scanning electron microscopy studies showed that raw chickpeas have a tightly packed structure with no air spaces, while roasted chickpea seed cotyledons have large air spaces resulting from water imbibition during soaking. This, in turn, increases vapor pressure during heating, causing steam to be produced and resulting in the expansion of chickpeas [146]. Roasting transforms carbohydrates into reducing sugars, which react with amino acids to produce a desirable color and flavor for consumers. The Maillard reaction during roasting generates brown pigments, leading to a decrease in the "*L*" value and an increase in the "*a*" and "*b*" values. The aroma and taste of roasted grains are created through the synthesis of esters and acid molecules [147]. During intense roasting at high temperatures, amino acids undergo oxidative decarboxylation in the presence of lipid peroxidation products. This process increases conjugated amines, leading to elevated levels of biogenic amines [148]. Prolonged roasting also reduces antioxidant activity due to the degradation of phenolic components [149].

Roasting chickpeas induces structural changes in their proteins, contributing to the characteristic taste, texture, and aroma of roasted chickpeas. These changes, while predominantly preserving the primary amino acid sequence, are pivotal for understanding the technological transformation during roasting [150]. In terms of primary structure, roasting generally maintains the amino acid sequence of chickpea proteins. However, heat application can initiate Maillard reactions, creating new compounds and enriching the flavor complexity of roasted chickpeas [151]. The secondary structure of chickpea proteins is affected as heat disrupts hydrogen bonds stabilizing elements such as α-helices and β-sheets, resulting in the unfolding or rearrangement of secondary structures. These changes can influence physical properties such as solubility and gelation ability [152]. Initially, roasting can enhance solubility by exposing hydrophilic regions, allowing for better interaction with water molecules. However, prolonged roasting may lead to protein aggregation due to hydrophobic interactions, reducing solubility [153]. When it comes to gelation, roasting can significantly affect the gelatinization process, primarily through altered water-binding properties, competitive water absorption with starch granules, and potential protein-starch interactions [154]. Tertiary structure modifications also occur, with heat-disrupting noncovalent interactions such as hydrophobic and electrostatic interactions, as well as disulfide bonds. This disruption leads to partial or complete unfolding of the tertiary structure, altering protein shape and exposing hydrophobic regions [155]. Roasting-induced changes in protein structure can impact functional properties, including interactions with other molecules or enzymes. The extent of these changes depends on roasting conditions such as temperature, duration, and chickpea moisture content [156]. Elevated temperatures result in extensive denaturation, disrupting secondary and tertiary structures, while longer roasting times can increase these structural alterations, leading to increased protein aggregation and potentially diminished solubility [145]. Additionally, the moisture content of chickpeas before roasting can impact protein functionality, with controlled moisture aiding in protein gelation but excessive moisture potentially initiating Maillard reactions [157]. Furthermore, roasting can influence the surface chemistry of chickpea proteins, impacting their interactions with other molecules and enzymes, thereby affecting the texture and structure of food products [158]. Additionally, the composition of chickpea proteins, including their amino acid sequences and interaction patterns, influences their susceptibility to heat-induced changes [159].

Roasting chickpeas has a transformative effect on their protein content and sensory qualities. During the roasting process, the Maillard reaction and caramelization generate a nutty and toasty aroma, leading to a richer and more complex flavor [145]. The development of savory, nutty, and slightly sweet notes makes roasted chickpeas more palatable and enjoyable. Additionally, changes in texture, such as increased crispiness and crunchiness, contribute to the overall sensory appeal. While roasting can alter the solubility of chickpea proteins, it can enhance their digestibility and improve their flavor [160]. However, it is essential to carefully control the roasting time and temperature to prevent overroasting, which can result in a burnt or bitter aroma [161].

Chickpea protein, roasting pretreatment, emerges with distinct health advantages rooted in the transformative effects of the roasting process. The enhanced digestibility of chickpea protein after roasting facilitates improved nutrient absorption, ensuring a readily available source of essential amino acids vital for various physiological functions [24]. Roasted chickpea protein also exhibits antioxidant properties, potentially offering protection against oxidative stress. Furthermore, the potential impact on appetite regulation and blood sugar control, combined with its contribution to muscle health, is noteworthy [72].

The study of Mesfin et al. [162] found that roasting Arerti variety chickpeas at 150°C (30 min) and 180°C (15 min) reduced protein content by 4.6% and 4.2%, while the Natoli variety showed an increase of 0.29% and 2.32%. Heat denaturation during roasting led to amino acid polymerization, reducing protein solubility. Both varieties exhibited the highest water-holding capacity at 150°C due to unfolded protein molecules exposing hydrophilic groups [163]. At 150°C, Arerti chickpea protein showed an 8.7% increase in oil-holding capacity. Solubility increased at 150°C but decreased at 180°C for both varieties due to protein inactivation. Emulsifying capacity decreased with roasting, likely due to protein fragmentation. Foaming capacity increased at 150°C, attributed to controlled heating, but decreased at 180°C, indicating adverse effects on protein functionality [164, 165].

The research conducted by Jogihalli et al. [166] explored the effects of roasting chickpeas at temperatures ranging from 250 to 350°C at a constant time of 6 min. Grains roasted at 350°C exhibited the highest puffing and expansion indices with the lowest length/width ratio. The color of chickpea flour shifted from light to dark, accompanied by increased "*a*" and "*b*" values. Functional properties, including water absorption and oil absorption, increased from 1.97 to 2.99 g/g and 1.25 to 1.81 g/g, respectively. Total flavonoid content decreased by 10%, while total phenolic content and antioxidant activity increased by 46% and 60%, respectively. FTIR and DSC analyses revealed changes in functional groups and starch crystallinity.

3.3.2. Extrusion. Extrusion is a thermal processing method that utilizes elevated temperatures and mechanical shear to force premixed food through a die, resulting in the creation of an extruded product. The die's size determines the final size of the extrudate [167]. Extrusion cooking is frequently used to produce snack foods, which exhibit specific characteristics such as crunchiness, crispy texture, taste, and flavor, resulting from the evaporative process that takes place as the material escapes the extruder die [168]. This thermal processing method is more widely accepted due to its ability to inactivate antinutritional ingredients, retain a substantial amount of nutrients, and provide textural qualities to the product [169]. During extrusion cooking, various biochemical transformations take place, including starch gelatinization, protein degradation, enhanced iron bioavailability, and removal of antinutritional factors [170]. The quality of the final product in extrusion cooking is influenced by several factors, such as temperature, feed moisture content, and screw speed. Studies have demonstrated that extrusion cooking can increase protein digestibility by denaturing protein at a higher temperature, resulting in a greater surface area available for enzymatic activity [171]. Chickpea flour, along with other pulses and cereal flours, is frequently employed in the production of snack foods. Starch plays a crucial role in the raw materials used in extrusion cooking, imparting the final product with its desired crunchy and expanded texture. The barrel temperature and feed moisture content are the primary factors influencing the biochemical changes in starch during the extrusion process [146]. Temperature increases result in a rise in the percentage of damaged starch. During extrusion cooking, the starch's crystalline structure changes towards an amorphous state, and the insufficient moisture content in the feed, coupled with significant shear stress, can lead to the dextrinization of starch [172]. The extrusion process enhances the starch's digestibility by breaking down covalent bonds [173]. Among various processing methods such as autoclaving, gamma irradiation, and roasting, extruded products demonstrate the highest protein digestibility [174]. Extrusion processing leads to a decrease in chickpea flour's protein solubility while increasing its water retention capacity at the cost of foaming ability [175, 176].

During the extrusion process, chickpea proteins undergo significant structural changes that profoundly impact the textural, functional, and nutritional properties of the resulting extruded products. While the primary amino acid sequence remains largely unaltered, extrusion induces various modifications in protein structure. In terms of primary structure, chickpea proteins maintain their amino acid sequence during extrusion [177]. However, elevated temperature and shear forces can trigger chemical reactions such as Maillard reactions and disulfide bond rearrangements, contributing to flavor development and protein cross-linking. The secondary structure of chickpea proteins is notably affected by extrusion. The combination of high temperature, pressure, and shear forces disrupts hydrogen bonds that stabilize secondary structural elements, leading to the unfolding or rearrangement of alpha-helices and beta-sheets [178]. Extrusion also impacts the tertiary structure as it disrupts noncovalent interactions that stabilize protein folding. This disruption can result in partial or complete unfolding of the tertiary structure, altering protein shape and exposing hydrophobic regions. These changes significantly influence functional properties such as solubility, emulsifying capacity, and gelation ability [179]. The extent of these structural modifications depends on extrusion conditions, including temperature, moisture content, screw configuration, and residence time. Higher temperatures and longer residence times tend to induce more pronounced changes. Additionally, the initial composition and structure of chickpea proteins influence their response to extrusion processing [180].

Extrusion processes introduce high temperatures, and short processing time can lead to Maillard reactions, resulting in roasted, nutty, or toasty aromas and flavors. This can modify the overall odor and aroma profile, reducing any raw or beany notes commonly associated with legumes [181]. Additionally, the texture of chickpea protein can be altered during extrusion, making it crisper or more brittle, which can impact the overall sensory experience [182]. The flavor profile of extruded chickpea protein is more processed and neutral compared to other methods, featuring a slight toasted or cooked quality [181]. Extruded chickpea protein is commonly used in the production of meat alternatives, textured vegetable protein, and snack products [178].

Extrusion pretreatment of chickpea protein presents notable health benefits owing to its distinctive processing method. Through high-temperature, short-duration cooking, extrusion enhances the digestibility of chickpea protein, facilitating optimal absorption of essential nutrients in the digestive tract [65]. The resultant product often boasts a balanced amino acid profile, providing a comprehensive set of essential amino acids crucial for overall health, muscle synthesis, and immune function. Extrusion contributes to a reduction in antinutrients, such as phytic acid, potentially improving the absorption of vital minerals like iron and zinc [183].

Three distinct chickpea extrusion conditions denoted as E450, E700, and E580 were investigated under different processing parameters. E450 utilized 143°C, a screw rotational speed of 450 rpm, and 15.6% processing moisture; E700 used 150°C, a screw rotational speed of 700 rpm, and 15.6% processing moisture, while E580 employed 22.5% processing moisture at 150°C and a screw rotational speed of 580 rpm [165, 184–186].

In a study, it was found that protein, total starch, and ash content in chickpea extrudates did not significantly differ from unextruded chickpea protein. However, extrudates exhibited lower fat content, with E450 and E700 showing up to a 62% decrease due to mechanical pressure, high temperature, and limited tempering water causing fat release (Table 2). Increased screw speed in E450 and E700 enhanced shear and SME, potentially leading to tissue disruption and oil release. Higher temperatures reduced oil viscosity, separating it from the matrix. More water in E580 reduced SME, resulting in less visible fat breakdown [187]. Extrudates E450 and E700 had higher insoluble dietary fiber levels than E580, while unextruded flour resembled E450 in insoluble dietary fiber. E450 had lower soluble dietary fiber, whereas unextruded flour had more. Elevated temperature and screw speed in E450 and E700 caused higher shear stress, releasing fragments from dietary fiber fractions and increasing soluble dietary fiber. E580, with higher moisture, exhibited 13% less soluble dietary fiber than E700 [165, 184–186].

The extrusion process significantly influenced water-holding capacity and foaming capability. Extrudates had higher water-holding capacity than unextruded protein, attributed to starch gelatinization [146]. E580 had the highest water-holding capacity due to higher moisture and temperature. However, extruded flour exhibited reduced foaming capability compared to unextruded flour due to protein aggregation and decreased protein solubility, hindering interaction with air bubbles during whipping [152].

Table 2: Effect of processing condition on chickpea ingredient.

Treatment	Effect on chickpea	References
Solid-state fermentation using *Cordyceps militaris SN-18* and lactic acid bacteria strain (*Pediococcus pentosaceus strain* VMCU76F)	Enhanced protein content by 19.43% Increased emulsifying ability and stability by 73.79% and 12.30% Decreased pH of dough 6.6 to 4.2 (24 h) Enhanced total phenolic content by 119% Increased water holding capacity by 67% Decrease in phytic acid, stachyose, and raffinose by 17%, 99.1%, and 88.3%	[138]
Germination (24 to 72 h)	Increased protein solubility by 2.79 to 6.67%. (24 h) Enhanced protein digestibility by 6.25% (48 h) Protein content increased by 4.08 to 4.36% (24 h) Decreased in fat content by 45.33 to 49.79% Reduced ash content by 15.72 to 30.25% (24 h and 48 h) Increased fiber content by 61.36 and 66.66% (24 h) Increased the water holding capacity by 21.24% and 13.88% (24 h) Oil holding capacity increased by 16.39% (24 h) Emulsion capacity increased by 16 to 23.18% (72 h) Foaming capacity increased by 34 to 39.5% (48 h) Enhanced total phenolic content by 16.2 to 76.6%. (24 and 72 h) The flavonoid content increased by 43.60 to 171% (24 to 72 h) Reduced phytate content by 18.6% (72 h) Reduced tannin content by 8.3 to 40.4% (24 h)	[108]
Roasting (150°C, 30 min)	Protein content decreased by 4.6% Fat content reduced by 27.11 to 46.96% Moisture content increased by 11.98 to 28.33% Enhanced fiber content by 86.4 to 207.14% Increased oil holding capacity by 8.7% Enhanced protein solubility by 12.6 to 14.6% Reduced emulsifying capacity 9.85 to 10.14% Increased foaming capacity 18 to 26.31% Enhanced phenolic content by 25.48 to 59.34% Total flavonoid content 73.7 to 142.2% Phytase content decreased by 19.9 to 41.25% Tannin content reduced by 19.9 to 41.25%	[164, 165, 185]

Table 2: Continued.

Treatment	Effect on chickpea	References
Roasting (180°C, 15 min)	Reduced protein solubility by 5 to 25% Total flavonoid content 80.5 to 138.6% Protein content decreased by 4.2% Fat content reduced by 27.12% Moisture content increased by 1.19 to 29.34% Enhanced fiber content by 90.9 to 192.8% Reduced oil holding capacity Reduced emulsifying capacity 16.89 to 17.38% Decreased foaming capacity 31.57 to 72% Enhanced phenolic content by 45.80 to 73.41% Phytase content decreased by 40.1 to 49.94% Tannin content reduced by 40.1 to 49.94%	
Soaking (12 h, 27°C)	Protein content increased by 1.59% Oil content increased by 18.81% Enhanced protein digestibility by 12.81% Reduced tannin and phytate content by 14.21 to 21.68 and 22.72 to 49.79% Decreased the mineral contents like zinc, iron, and calcium by 0.78, 3.97, and 2.26% Water holding capacity and oil holding capacity increased by 1.35 and 1.05%	[64, 76–78]
Extrusion (15.6% processing moisture, at 143°C and 450 rpm)	Decreased moisture content by 77.14% Reduced protein content by 4.8% Decreased fat content by 61.87% Increased starch content by 1.04% Decreased ash content by 1.5% Insoluble dietary fiber decreased by 2.69% Soluble dietary fiber increased by 152%	[165, 184–186]
Extrusion (15.6% processing moisture, at 150°C and 700 rpm)	Decreased moisture content by 75.58% Reduced protein content by 1.81% Decreased fat content by 58.52% Increased starch content by 1.58% Decreased ash content by 0.38% Insoluble dietary fiber increased by 2.69% Soluble dietary fiber increased by 270.75%	
Extrusion (22.5% processing moisture, at 150°C and 580 rpm)	Decreased moisture content by 77.31% Reduced protein content by 3.68% Decreased fat content by 28.59% Increased starch content by 1.493% Decreased ash content by 66.18% Insoluble dietary fiber decreased by 20.88% Soluble dietary fiber increased by 166.98%	

In summary, roasting and extrusion methods offer significant advantages for processing chickpeas. Roasting enhances sensory qualities and nutritional properties, including protein and fiber content, while extrusion improves nutrient retention and iron bioavailability. However, both treatments may affect protein solubility and functional characteristics. The choice between them depends on desired product attributes and processing goals. Both methods have proven effective in enhancing chickpea products, but further research can optimize these techniques for top-quality outcomes.

4. Applications of Chickpeas in Food Products

Chickpea protein stands out among other pulse proteins such as pea and soybean due to its distinctive attributes, making it a versatile ingredient across a wide range of food applications. Notably, chickpea protein exhibits superior foaming capacity, stability, thermal expansion, and emulsion stability compared to its counterparts, making it an essential component in the production of chickpea-based bread. These qualities contribute to the high specific volume and enhanced nutritional attributes of chickpea-based bread products (20% chickpea flour) [188]. Furthermore, the incorporation of chickpea flour (6% chickpea protein) into gluten-free batter has been found to enhance the storage modulus, indicating improved structural stability. However, cohesiveness tends to decrease during the storage of chickpea bread, suggesting potential textural changes over time [189]. The versatile applications of chickpeas in various food products are illustrated in Figure 2.

In the realm of bread-making, the inclusion of chickpea flour (20%) in a blend with wheat flour has profound effects on the rheological characteristics of the dough. Farinograph tests on dough with varying proportions of chickpea and wheat flour reveal a rising trend in water absorption capacity as chickpea flour content increases. However, dough stability and development show a downward trend [190]. Moreover, increasing the proportion of chickpea flour leads to a reduction in gluten content within the dough, resulting in weaker dough. Extensograph testing shows that the incorporation of chickpea flour enhances dough extensibility. Interestingly, when chickpea flour substitutes a portion (30%) of wheat flour, the rheological properties of the dough improve significantly [191].

Dehusked chickpea flour finds (70 to 100%) wide application in traditional foods such as chilla, dhokla, and boondi, where it is blended with water to create a thick batter or suspension. The rheological properties of chickpea flour suspension have been investigated extensively, displaying shear-thinning behavior characteristic of non-Newtonian fluids, with apparent viscosity decreasing as the shear rate increases [190]. The addition of salt to the batter induces a plasticization effect, enhancing flow properties during preparation. As salt concentration increases, the solubility of chickpea protein's salt-soluble fraction, especially globulins, is heightened, leading to reduced viscosity upon incorporation into the continuous phase. This rheological behavior is consistent with that observed in chickpea protein isolates [192].

Boondi, a popular snack, is created by deep-frying droplets of chickpea flour suspension in oil. The frying process involves simultaneous heat and mass transfer through convection and conduction [193]. Chickpea flour batter concentration of around 40–42% results in superior product attributes [194]. Boondi can be enjoyed in sweet or spiced versions, as well as in savory snacks like chaat or salad toppings. Boondi raita, a common side dish, involves adding plain or spiced boondi to curd, seasoned with salt, roasted cumin powder, and other spices. Boondi is versatile and adaptable to various preparations and applications [195].

Sattu, or roasted chickpea flour, is a popular summer beverage known for its cooling effect on the body and benefits for individuals with gastrointestinal ulcers. It is nutritionally rich, cost-effective, and created by blending various cereals and pulses, supplemented with lime juice, salt, sugar, and spices. Roasted or germinated cereal and pulse flour augment nutritional profiles [196–198] (Table 3). Roasted chickpea flour's physical and thermal characteristics are influenced by moisture content and particle size. Elevated moisture content decreases flowability but increases bulk and true density, while thermal conductivity rises with increasing moisture content [199]. Smaller particle size leads to higher specific heat and thermal diffusivity, with increasing moisture content corresponding to enhanced thermal diffusivity [202].

Chickpea flour is widely applied in various food products, including bread, cookies, biscuits, pasta, and yogurt, enhancing nutritional value, probiotic growth, antioxidant capacity, and viscosity (Grasso et al., 2022). Incorporating chickpea flour (6%) into pasta, typically made from durum wheat semolina, improves its nutritional profile, reducing the glycemic index while boosting protein, fat, and mineral content [203]. The incorporation of chickpea flour also leads to shorter cooking times, reduced water absorption, and enhanced adhesiveness. While whole chickpea flour has a negative impact on cooking quality, dehulled chickpea flour improves it [204]. Composite pasta containing semolina and chickpea flour shows reduced starch gelatinization compared to semolina pasta, attributed to the protective matrix formed by chickpea flour's nonstarch polysaccharides, fat, and protein [205]. The nonstarch polysaccharides, comprising dietary fiber such as pectins and hemicelluloses, form a physical barrier around starch granules, inhibiting their access to water during cooking [206]. Simultaneously, the abundant proteins in chickpea flour interact with starch through hydrogen bonding and electrostatic forces, creating a protective matrix that hinders starch granules from fully swelling and gelatinizing [207]. The presence of fat in chickpea flour further contributes to this protective effect by coating starch granules with a hydrophobic layer, impeding water absorption. This complex matrix of nonstarch polysaccharides, proteins, and fat acts as a shield, collectively reducing the extent of starch gelatinization [205].

During the weaning phase, the transition from mother's milk to less nutritious food can lead to protein energy malnutrition (PEM) in children. To address childhood malnutrition, cost-effective and nutritious weaning foods are

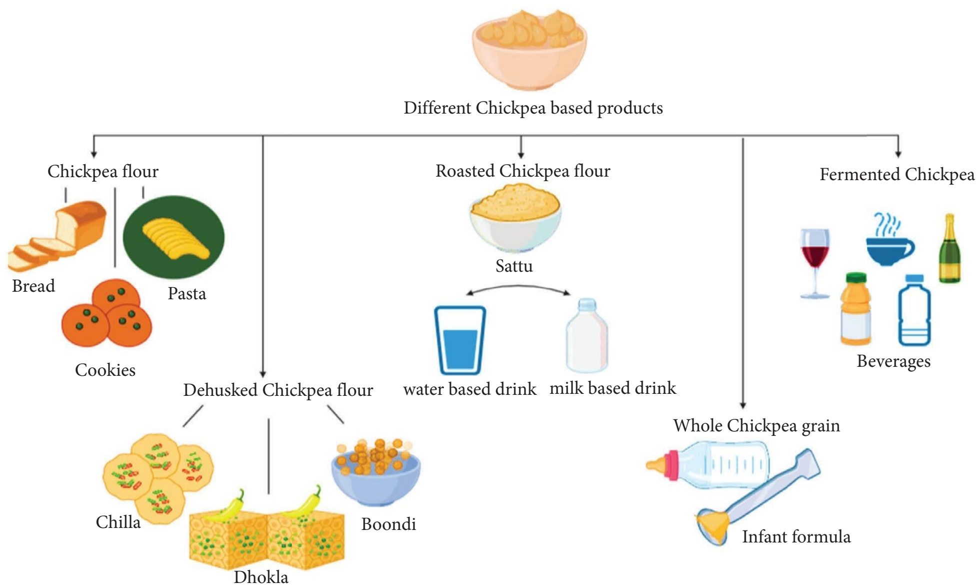

Figure 2: Application of chickpea seeds in various food products.

essential. Whole chickpea grains have been explored in developing infant formula [208]. Utilizing germinated chickpeas followed by boiling, drying, and dehulling is an efficient method for producing fortified infant follow-on formula enriched with minerals and vitamins [209]. Formulating weaning food involves blending extruded flours of maize and chickpea along with skimmed milk powder and sugar, enhancing in vitro starch and protein digestibility. Additionally, the combination of malted, roller-dried, or popped barley and chickpea holds promise in weaning food formulation [210].

The rising demand for plant-based milk has led to the exploration of legumes, particularly chickpeas, as an alternative to cow's milk in nutrient-rich meal-replacement beverages [211]. Plant-based beverages derived from chickpeas can be beneficial for individuals with lactose intolerance. Blending chickpea and coconut extracts results in a favorable nutritional profile, especially high protein content and calcium levels, surpassing other substitutes. A blend of 70% chickpea extract and 30% coconut extract shows the most promising outcomes in terms of nutritional quality and sensory attributes. Both fresh and fermented chickpea beverages hold potential as substitutes for soy milk and cow's milk [212, 213]. Chickpea flour can also act as a prebiotic and thickening agent in producing stirred bio-yogurt. Incorporating chickpea flour (2.5%) enhances viscosity, antioxidant activity, probiotic viability, pH reduction during storage, and protein network strength of the yogurt [198].

Chickpea flour's incorporation in pasta products with a low glycemic index makes them suitable for individuals with diabetes [214]. Chickpea pasta, commercially available, is produced by numerous global food companies. Incorporating chickpea flour effectively slows the release of sugars into the bloodstream [215]. Additionally, chickpea flour is used in combination with other ingredients to create puff snacks and crisps available in retail markets. Incorporation of chickpea protein concentrate (5%) enhances the organoleptic properties of merguez and soya sausages, offering improved color stability, reduced lipid oxidation, and antioxidant properties [197]. In bread production, partial replacement of wheat flour with chickpea protein concentrate enhances mass volume, potentially attributed to chickpea protein's water-holding capacity. Chickpea protein's gelling properties make it a promising alternative to soy for creating sausage-type meat analogs, with reliable emulsifying and foaming stability [216]. Chickpea protein isolate's use for microencapsulation of folate demonstrates its potential in this emerging technology, offering advantages such as biocompatibility, increased loading capacity, reduced toxicity, and enhanced folate stability [15]. Mayonnaise formulations benefit from the addition of 3% chickpea protein isolate, enhancing acceptability in terms of texture, aroma, flavor, and appearance [196].

Byproducts from chickpea cultivation and processing, including bran from dehulling crop residues and chickpea hay, are valuable as animal feed [200]. Chickpea hulls hold potential as a fiber and phenolics source, offering antioxidant capacity for innovative high-value products. Phenolic compounds extracted from chickpea hulls serve as natural antioxidants in meat to prevent lipid oxidation. They are preferred by consumers over synthetic antioxidants [217]. Chickpea hulls also serve as a natural textile dye for clothing fabrics. The solvent-free dye, extracted from chickpea hulls, contains phenols, tannins, and flavonoids, coloring cotton, wool, and silk garments in an environmentally friendly manner [201]. Chickpea straw, a byproduct of harvesting, is used as animal feed, enhancing feed nutritional value for ruminants as an alternative to hay or silage. In addition to its

Table 3: Application of chickpea components in food products.

Chickpea component	Food products	Chickpea component ratio	Application	References
Chickpea flour	Bread	20% (chickpea flour)	Enhance rheological properties Enhance water holding capacity Improve dough stability Higher mass volume Increased water-holding capacity Increased protein content	[188]
	Gluten-free noodles and pasta	6% (chickpea protein)	Enhanced the protein content Increased antioxidant properties Decreased the glycemic index Decreased starch digestibility Improved the nutritional profile by 25%	[189]
	Gluten-free muffins	14% (chickpea protein isolate)	Decrease the crust hardness Decrease browning index	[17]
	Capsule and micronutrient supplementation	1.6% (chickpea protein isolate)	Increase the biocompatibility Nutritional advantage Improve loading capacity Reduce toxicity Improve stability of folate vitamin B9	[15]
	Mayonnaise	3% (chickpea protein isolate)	Enhance the acceptability in terms of texture, aroma, flavor, appearance	[196]
	Merguez and soya sausage	5% (chickpea protein concentrate)	Increase process yield Improve textural and sensorial properties Improved color stability Decreased water vapor formation in the dough	[197]
	Biscuit	40% (chickpea flour)	Enhance the nutritious values with low digestibility Improve textural properties Increased protein content	[188]
	Snacks	30–70% (chickpea flour)	Increases the nutritional quality Improve physical properties Enhanced sensory qualities Increased storage stability	[85]
	Yogurt	2.5% (chickpea flour)	Enhanced the growth of probiotic bacteria Increased antioxidant capacity and viscosity	[198]
Dehusked chickpea flour	Chilla, dhokla, and boondi	70 to 100% (chickpea flour)	Better product quality Improve flow properties during preparation Enhance flavor Increases shear rate	[190]
Roasted chickpea flour	Sattu	—	Enhanced the nutritional value Increase thermal diffusivity Decreased particle size	[199]
Chickpea hay	Animal food	—	Increased nutritional value	[200]

Table 3: Continued.

Chickpea component	Food products	Chickpea component ratio	Application	References
Chickpea hull	Textile dye	2% (Chickpea hull)	Solvent free dye Making it environment friendly	[201]

applications in food products, animal feed, food additives, and the textile industry, chickpea protein byproducts find use in biodegradable packaging and cosmetics production [218].

The use of chickpea protein isolate at 14% in gluten-free muffins contributes to a decrease in crust hardness and browning index, offering an appealing texture and appearance [17]. For capsule and micronutrient supplementation (1.6%), chickpea protein isolate exhibits advantages in terms of biocompatibility, nutritional benefits, loading capacity improvement, and reduction of toxicity. Moreover, biscuit formulations with 40% chickpea flour exhibit improved nutritional values, low digestibility, enhanced textural properties, and increased protein content [188]. Snacks, with 30–70% chickpea flour, see increased nutritional quality, improved physical properties, enhanced sensory qualities, and increased storage stability [85].

In conclusion, chickpea protein's exceptional qualities make it a versatile ingredient with diverse applications in the food industry. Its functional properties, nutritional benefits, and potential contributions to sustainability make chickpea protein an attractive choice for food product innovation and development. From enhancing the quality of bread and pasta to serving as an alternative to dairy milk and contributing to weaning food formulations, chickpea protein continues to play a significant role in shaping the future of the food industry. Its byproducts further extend its utility, finding applications in animal feed, textiles, antioxidants, and beyond. As the demand for plant-based and nutritious food options grows, chickpea protein and its derivatives are poised to remain at the forefront of these developments.

5. Future Challenges and Perspectives

The impact of conventional pretreatments on chickpea protein's nutritional and functional attributes is significant for health and innovative food products. Future challenges include optimizing techniques for preserving nutritional quality, identifying efficient parameters, enhancing sensory attributes, and developing safe and hypoallergenic products. Integrating chickpea protein into plant-based alternatives, dairy substitutes, and gluten-free items can cater to the growing demand for healthier, sustainable options. Addressing these challenges will unlock the potential of chickpea protein, creating impactful food products that benefit human health and nutrition.

6. Conclusion

Chickpea's nutritional richness, protein content, and low glycemic index contribute to its role in enhancing global food security and health. Pretreatments such as roasting, extrusion, and fermentation improve functional properties and reduce antinutritional factors. Chickpea protein is utilized in various foods, boosting their nutritional value and sensory properties. Encapsulation enhances nutrient stability, while chickpea flour benefits gluten-free products. Health-wise, chickpeas aid in cholesterol management, diabetes prevention, and weight loss. Incorporating chickpeas into diets can address malnutrition and promote public health, making them a vital resource for nutrition and well-being.

Data Availability

Data are available upon reasonable request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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