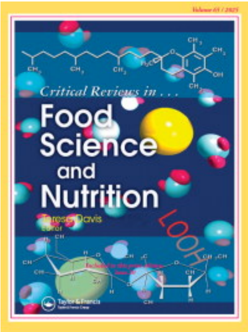

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REVIEW ARTICLE

Green wheat Freekeh: evolution from traditional cereal to sustainable future food

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ABSTRACT
Freekeh, a traditional Middle Eastern cereal derived from wheat, is gaining global recognition as a climate-resilient, nutrient-dense alternative to commonly consumed staples such as white rice and refined wheat. It offers a compelling solution to pressing challenges in nutrition, sustainability, and food security. Compared to conventional grains, Freekeh's cultivation requires less irrigation and fertilizer, supporting more sustainable agricultural practices without compromising nutritional value. This review explores Freekeh's history, eco-friendly production, and compositional profile—highlighting its high protein (11%–15%), dietary fiber (12%–19%), and starch (45%–68%) content. It is also a valuable source of micronutrients including potassium (369–451 mg/100 g), magnesium (160–202 mg/100 g), phosphorus (412 mg/100 g), and B vitamins, as well as antioxidant vitamins C and E. Bioactive compounds such as ferulic acid, lutein, and zeaxanthin further enhance its functional potential. Freekeh's low glycaemic index and cholesterol-lowering effects make it particularly relevant in the context of non-communicable disease prevention. While it contains gluten, further research is needed to assess its allergenic potential and phytate-related impacts on mineral bioavailability. This review highlights the timely need to explore Freekeh's consumer acceptance, processing properties, and industrial applications positioning it as a promising ingredient in the transition toward more sustainable and health-oriented food systems.

KEYWORDS
Freekeh; green wheat; immature wheat; nutritional benefits; sustainable agriculture

1. Introduction

Cereals are crucial in combating hunger, serving as the primary staple food worldwide and providing the most energy and essential nutrients for human nutrition. Freekeh (also spelt Frekeh, Frikeh, or Freekah), is a traditional Middle Eastern cereal made from early harvested common wheat (*Triticum aestivum*) or durum wheat (*Triticum durum*). It is gaining global attention due to its unique attributes, including sustainability, ease of production, exceptional nutritional profile, and health benefits. Freekeh presents an intriguing avenue for diversifying and enhancing food products. Freekeh is derived from wheat that is harvested prematurely, specifically at the conclusion of the milky stage. This occurs when both the culms (stems) and spikes (flowering parts) of the wheat are still green (Majzoobi et al. 2023). Green or immature wheat can be consumed fresh in various products, although its shelf life is significantly limited. To prolong its shelf life and enhance its flavor profile, green wheat is commonly frozen, dried or roasted (Al-Mahasneh and Rababah 2007; Boukid 2021). The appearance of fresh green wheat, roasted Freekeh and mature wheat obtained from the same source is given in Figure 1. The size and weight of the Freekeh kernel varies depending on the variety, growth conditions, harvest time, and post-harvest processing conditions (Al-Mahasneh and Rababah 2007; Özkaya et al. 1999).

Currently, Freekeh is not listed as a distinct commodity in the Food and Agriculture Organization (FAO) statistical database, and no separate global production, trade, or consumption data are available. While FAO provides detailed statistics on major cereal crops such as wheat, rice, and maize, Freekeh, being a traditional product made from green durum wheat, remains categorized under the general wheat data. However, FAO has recognized the cultural and economic relevance of Freekeh in specific regions, such as in Lebanon, where its production has been linked to rural development and women's empowerment. This gap in statistical coverage highlights the need for improved global documentation and monitoring of emerging ancient grains like Freekeh to better support their commercial and nutritional potential.

Freekeh, being an immature grain, is considered more environmentally friendly than fully mature wheat due to its shorter growth cycle, which reduces the need for irrigation,

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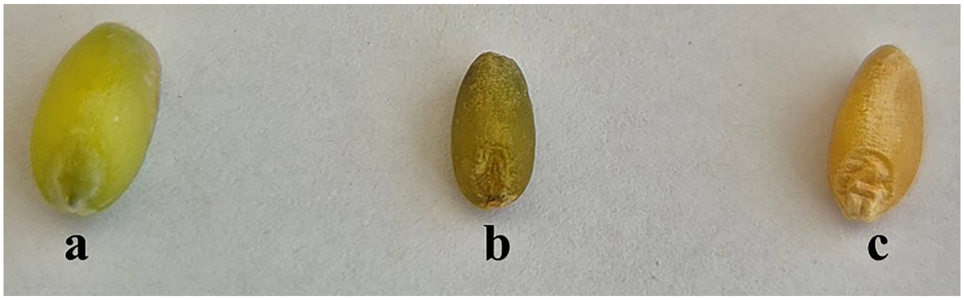

Figure 1. Appearance of fresh green wheat (a), Roasted Freekeh (b), and mature wheat (c) all obtained from *Triticum aestivum* from the same farm and environmental conditions. Grains were provided by Edlyn Foods Pty Ltd, Melbourne, Australia.

pesticides, and fertilizers. Additionally, whole grains are valued for their rich nutrient profile and bioactive compounds, offering significant health benefits. As a result, Freekeh supports the development of sustainable food systems and presents a viable solution to food insecurity amid ongoing climate change (Majzoobi et al. 2023).

The main objective of this review article was to critically assess the potentials of Freekeh in meeting current and future food product demands. By examining its nutritional composition, health benefits, food applications, allergenicity and intolerance, this comprehensive review article sheds light on Freekeh's capacity to meet the evolving needs of consumers and the food industry. Furthermore, it seeks to explore the positioning of Freekeh in comparison to commonly available competitive grains. Exploring the potential applications of Freekeh in various cuisines and product formulations can provide valuable insights into harnessing the benefits of this traditional food for addressing pressing food challenges of the present and those that will emerge in the future.

2. History and origin of Freekeh

Freekeh is an ancient whole grain, valued for thousands of years and widely regarded as a symbol of resilience and adaptability. Archaeological evidence indicates that Freekeh likely originated in the Middle East, as well as being a staple in China for over 1000 years (Zhang et al. 2020). For centuries, Freekeh has been an integral part of specific regions in the Mediterranean as well as Middle Eastern countries. It has been depicted in symbolic representations of sociohistorical narratives, and as such is a cultural artifact that connects communities. In the context of globalization, traditional foods like Freekeh have been adopted as an ethnic cuisine, adding culinary diversity and a sense of adventure. Manufacturers have standardized and adapted these foods to align with the culinary and gastronomic preferences of European countries (Boukid 2021; Mondal and Datta 2008; Tebben, Shen, and Li 2018).

3. World production; main producers

Reports indicate that an annual production of 250–300 thousand tons of Freekeh occurs in the Middle East, and that it is also gaining popularity as a food choice worldwide (Al-Mahasneh and Rababah 2007; Bayram 2008). Freekeh is primarily cultivated in farms and villages across Anatolia (Turkey), Lebanon, Jordan, Egypt, Iraq, Iran, Syria, Mesopotamia, and North Africa (Bayram 2008). In Northern Hemisphere countries, production typically occurs between May and July, during the immature stage before harvesting. Conversely, in Southern Hemisphere countries, such as Australia, the primary production period is during October and November.

Traditionally processed methods, such as drying or baking, have been employed in its preparation. Notably, in China over the past century, where it has been consumed directly as a food product, the fresh green wheat is highly popular as a medicinal cereal and is characterized by its chewy and slightly sweet texture (Bayram 2008; Zhang et al. 2020).

Freekeh exports are predominantly directed toward European countries, with a particular focus on countries having large populations of Turkish, Arabic, Syrian, Jewish, Middle Eastern, and Armenian populations. Key destinations include countries like France, Germany, Sweden, Spain, amongst others (Bayram 2008).

Despite its popularity, the price of Freekeh is relatively high for consumers (Bayram 2008). This high cost is attributed to the seasonal nature of the product and the comparatively lower production yields obtained, as it is harvested whilst still immature (Al-Mahasneh and Rababah 2007). The commercialization and industrialization of Freekeh remain comparatively limited compared to fully mature wheat. However, there is notable development with the emergence of commercial labels such as Green Wheat Freekeh™, an Australian brand dedicated to Freekeh production. Additionally, Freekeh is included in the database of whole grain content-based foods in Australia (Boukid 2021).

4. Agricultural considerations

In contemporary Freekeh production, durum wheat (*Triticum durum*, a tetraploid) is the preferred choice, although bread wheat (*T. aestivum*, a hexaploid) is also utilized. Durum wheat is particularly favored because the finest Freekeh is derived from the largest and toughest kernels (Aderibigbe et al. 2022). Among durum wheat varieties, *Zenit* and *Diyarbakır* spp. are commonly preferred due to their suitability in achieving high-quality Freekeh (Zhang et al. 2020). Figure 2 shows the appearance of fresh green wheat and roasted Freekeh obtained from the two main wheat varieties.

The changes in kernel composition as wheat matures have a direct impact on the characteristics of Freekeh. It is widely acknowledged that Freekeh processed from wheat harvested between the late milk-ripening stage (around 25–30 days post-anthesis) and the mid-dough-ripening stages are more appetizing than those processed at the fully ripe stage. This preference is likely attributed to the higher concentrations of free simple sugars present in the kernels during the earlier stages of maturation (Zhang et al. 2021a). The optimal time for harvesting wheat to produce green wheat is when some milky endosperm is extruded from a grain when it is squeezed between the thumb and forefinger. Selecting the right stage for green wheat production is crucial for achieving the desired quality characteristics. Harvesting and roasting wheat too early may result in grain collapse, while harvesting and then roasting too late may fail to impart the distinctive green color and flavor associated with green wheat (Al-Mahasneh and Rababah 2007). Harvest time significantly impacts the chemical composition and nutrient content of Freekeh and is a key factor in determining its overall quality and sensory properties. However, the optimal harvest time is often determined empirically, based on farmers' experience and knowledge, which needs to be integrated with experimental research to ensure consistency and quality. Pre- and post-harvest conditions and processing have a great influence on the Freekeh quality and nutritional profile which will be discussed in Section 6.

5. Production of Freekeh

5.1. Traditional production method

Freekeh is produced by traditional as well as modern methods. In the traditional and conventional method of processing green wheat, the process begins with cutting and gathering wheat sheaves in the morning. These are then left to air-dry for 2–4 h in an open area. Once sufficiently dried, the sheaves are arranged on clean ground or metal sheets and burned using the dried remnants of other crops, such as barley straw. Alternatively, some modern farmers opt for direct flame throwers fueled by butane. Throughout the burning process, the sheaves are regularly turned with a pitchfork to ensure even exposure to the green leaves and glumes. When the glumes are charred and tips of some grains show a slight blackening, the burning ceases, and the spikes are allowed to cool. After a few hours, the heads are threshed by feeding them into a threshing machine, often brought to the site for this purpose, and then cracked using a stone mill. The resulting fresh green wheat possesses a subtle sweetness, a chewy texture, and a desirable smokey flavor. A high-quality and premium product is characterized by the plumpness, a slight char, firmness when fresh, a green hue when dried, and minimal remnants of husks, glumes, and debris (Al-Mahasneh and Rababah 2007; Boukid 2021).

Green wheat can be marketed either immediately while fresh or in frozen form. Fresh green wheat is highly perishable and has a short shelf life. To extend its shelf life, the moisture content is reduced from 50% to 12% through drying. This crucial phase must be completed within a day after harvesting fresh green wheat to prevent spoilage. Drying can be achieved through natural air drying or roasting. For roasting, the grains are heated in an oven or in pans, resulting in a golden-brown color and a pleasant nutty flavor.

5.2. Industrial production method

The modern processing of large-scale quantities of Freekeh involves a continuous process comprising of four key steps (Figure 3): The first step involves roasting the collected sheaves by direct exposure to fire on a metal conveyor belt; step 2 involves threshing the roasted sheaves to separate the green wheat kernels from other residues;

Figure 2. The appearance of fresh green wheat (a) and roasted Freekeh obtained from grains from *Triticum aestivum* (b) and roasted Freekeh from *Triticum durum* (c). Grains were provided by Edlyn Foods Pty Ltd, Melbourne, Australia.

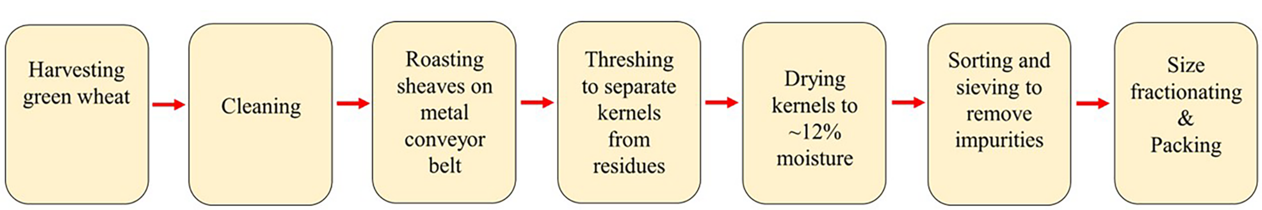

Figure 3. Process flowchart of Freekeh.

step 3 involves drying the threshed kernels to reach a moisture content of around 12%; and finally the final step involves sorting and sieving which are carried out to separate impurities (Al-Mahasneh and Rababah 2007). After grading of the grains according to their size, the roasted grains are packed and marketed as whole or cracked dry grains or further processed into retorted, ready to eat cooked grain products.

6. Chemical composition and health benefits of Freekeh compared to mature wheat

The chemical composition of Freekeh differs from mature wheat (see Table 1) due to its early harvest stage, reflecting the plant's adaptations for growth and survival. Immature wheat prioritizes rapid growth and energy metabolism, leading to higher moisture, more soluble protein and carbohydrates, simple sugars, and bioactive compounds such as polyphenols and antioxidants, which support photosynthesis and defense against environmental stresses, pests, and microbes. These differences influence digestibility, functional properties, and health benefits which have been explained below.

6.1. Carbohydrates

Starch constitutes the major carbohydrate in Freekeh, ranging from 45% to 50%, while mature wheat contains 60%–75% depending on the variety and harvest time (Zhang and Zhang 2019). Thus, Freekeh contains lower starch levels, which in turn reduces the availability of readily digestible starch for enzymatic digestion (Carsiraghi et al. 2006; Iametti et al. 2006). The starch in Freekeh consists of two distinct types of granules: A-type and B-type as shown in Figure 4. The A-type granules are disc-shaped and range from 10 to 35 µm in diameter, while the B-type granules are smaller, spherical, and have an average diameter of 1–10 µm. These granules form at different stages of the wheat grain development: A-type granules begin to form between 4 and 7 days after anthesis (DAA), while the B-type granules appear around 10–14 DAA. A third granule population, forming around 21 DAA, has also been identified in the wheat endosperm (Waduge et al. 2013). As a result, the small granules

Table 1. Comparison between the proximate composition of Freekeh, mature wheat and other emerging grains.

Grain type	Protein	Starch	Dietary Fiber	Minerals	References
Freekeh	11.94%–14.90%	45%–68%	12.88%–19.30%	Na: 4–12.5 mg/100 g Ca: 32–63 mg/100 g K: 369–451 mg/100 g Mg: 160–202 mg/100 g P:412 mg/100 g Cu: 0.49 mg/100 g Fe: 4.22 – 5.67 mg/100 g Zn: 2.55 – 3.79 mg/100 g	(Majzoobi et al. 2023; Özkaya et al. 2018; Saini et al. 2021)
Mature Wheat	11.90%–13.90%	60%–75%	12.21%–19.37%	Na: 5.40–7.38 mg/100 g Ca: 35.6–49.26 mg/100 g K: 370–458 mg/100 g Mg: 166–178 mg/100 g P: 421.78 mg/100 g Cu: 0.40 mg/100 g Fe: 4.34–4.02 mg/100 g Zn: 2.96–3.04 mg/100 g	(Biel et al. 2021; Özkaya et al. 2018; Vaher et al. 2010; Yang et al. 2012)
Quinoa	12%–23%,	58.1%–64.2%	2.0%–2.2%	Fe: 5.5 mg/100 g Zn: 1.8 mg/100 g Mg: 206 mg/100 g Cal: 32.9 mg/100 g K: 926.7 mg/100 g P: 383.7 mg/100 g	(Angeli et al. 2020; Satheesh and Fanta 2018)
Colored Rice	6.5%	85%–90%	6.76%–4.95%	Fe:71.08–111.84 g/kg Mn: 25.25–30.08 mg/kg Zn: 6.7 mg/100 g Cu: 6.05–7.13 g/kg Ca: 270.54–432.38 g/kg Mg: 1228.04–1140.28 g/kg	(Aini, Dwiyanti, and Salamah 2023; Rebeira et al. 2022; Zhu et al. 2024)
Wild rice	10%–15.5%	56%–79%	6.8%	Ca: 21–24 mg/100 g Fe: 1.60–3.17 mg/100 g Mg: 106–120 mg/100 g Mn: 0.93–1.45 mg/100 g P: 236–384 mg/100 g K: 145–244 mg/100 g Na: 1.34–5.86 mg/100 g Zn: 1.25–2.83 mg/100 g	(Majzoobi et al. 2023)
Chia seeds	17%		18%–30%	Ca: 456–631 mg/100 g P: 860–919 mg/100 g K: 407–726 mg/100 g MG: 335–449 mg/100 g Fe: 8.54 mg/100 g Zn: 3.7 mg/100 g	(Hrnčič et al. 2019; Kulczyński et al. 2019)

at full maturity are likely to include both those from 10 to 14 DAA and those from 21 DAA.

In contrast to Freekeh, mature wheat starch presents a different starch profile. A comparison between the starch properties of Freekeh and mature wheat harvested at 24–25 and 35–36 DAA reveals marked differences in starch characteristics. Scanning electron microscopy (SEM) studies show significant aggregation of B-type starch granules, likely due to the formation of amylose-lipid or starch-protein-lipid ternary complexes. This aggregation contributes to a lower predicted glycemic index (GI) for Freekeh, suggesting slower starch digestion compared to mature wheat. Furthermore, Freekeh has a lower amylose content than mature wheat, and both types of starch granules (A and B) in Freekeh exhibit higher protein and lipid contents, which may inhibit enzyme interactions and affect gelatinization during processing (Zhang et al. 2021a).

The differences in starch properties between Freekeh and mature wheat were further confirmed through *in vitro* starch digestion. Freekeh generally exhibited lower GIs than mature wheat, with B-Freekeh showing the lowest GI after 300 min. Additionally, Freekeh demonstrated higher gelatinization temperatures and enthalpies compared to mature wheat, indicating distinct thermal properties between the two. These findings underscore the potential of Freekeh, as a functional ingredient with lower GI and unique processing characteristics which could benefit health-conscious consumers. Given the rising demand for low-GI foods, Freekeh could be instrumental in managing chronic diseases such as diabetes, obesity, and cardiovascular diseases (Bresciani et al. 2023; Nour, Ionica, and Trandafir 2015; Saeva, Srikaeo, and Sopade 2023; Zhang et al. 2021a).

Fiber is another significant component of Freekeh, ranging from 12.88% to 19.30%, depending on the variety and maturation stage (Yang et al. 2012). Özboy et al. (2001) investigated the fiber content in Freekeh produced from two durum wheat cultivars (Duraking and Ege 88) at various stages of maturation, processed through roasting and boiling methods. The study found a significant reduction in fiber content in both cultivars as they matured, with reductions observed between 13 and 25 days post-anthesis. Additionally, both the boiling and roasting processes led to a decrease in fiber content, with up to a 4% reduction for both varieties. In comparison, mature wheat typically has lower fiber content than its premature green counterpart. A study on the soft to medium-hard wheat cultivar *Triticum aestivum L. cv. Keumkang* found that premature green wheat contained significantly higher dietary fiber (19.3%) compared to mature yellow wheat (14.3%). This indicates that earlier harvesting stages, such as those used for Freekeh, may offer higher fiber content compared to fully matured wheat, contributing to its enhanced nutritional profile and potential health benefits (Yang et al. 2012).

Freekeh is rich in fructans, a type of soluble dietary fiber that offers a range of health benefits. As a prebiotic, fructans promote the growth of beneficial gut bacteria, improving digestion and regularity. They also support cholesterol reduction by binding to bile acids and help regulate blood sugar, making Freekeh a valuable food for heart health and diabetes management. However, fructans can cause bloating and discomfort in individuals with Irritable Bowel Syndrome (IBS). Despite these potential side effects, the high fiber content of Freekeh, its enhanced mineral bioavailability, and its support for gut health has positioned it as a functional food

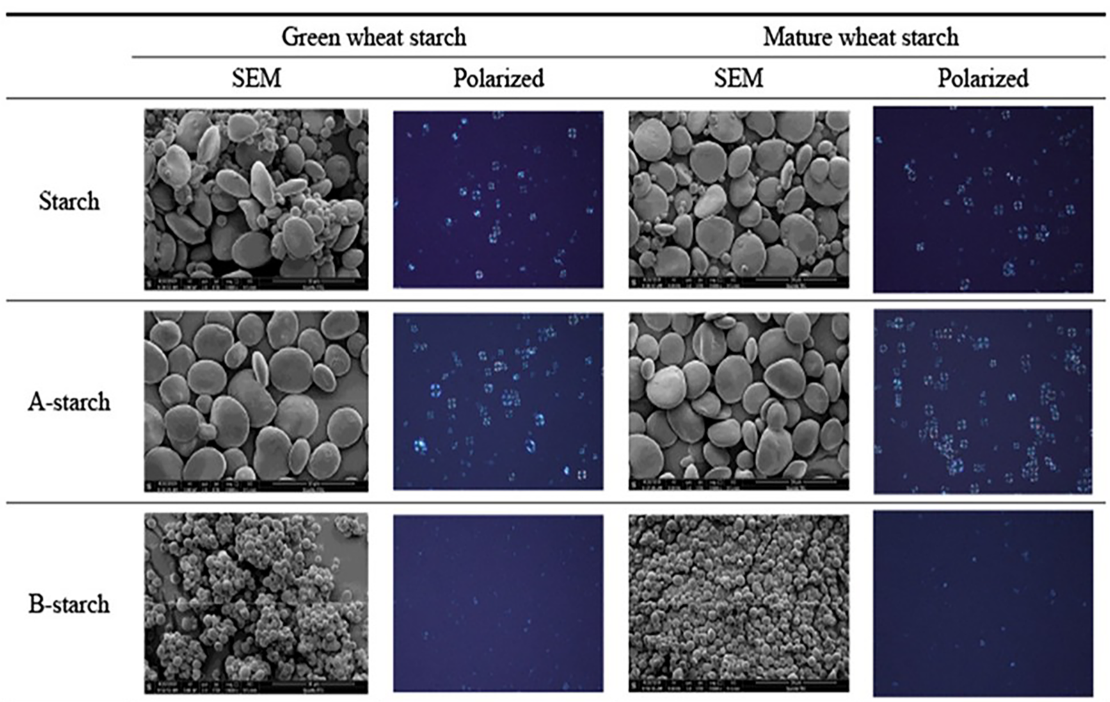

Figure 4. SEM images (3000×) and polarized light micrographs (200×) of green wheat starch (GWS) and mature wheat starch (MWS) and their isolated A- and B-starch granules (taken from Zhang et al. 2021a).

with significant nutritional advantages (Maskan and İbanoğlu 2002; Özboy et al. 2001; Özkaya et al. 2018).

The simple sugars in Freekeh have also been studied, with Yang et al. (2012) analyzing the sugar content in both green and mature yellow wheat of the *Triticum aestivum* L. cv. *Keumkang* variety. Their findings showed that green wheat had a significantly higher total reducing sugar content (1.56%) compared to mature yellow wheat (0.84%). The sucrose content was also notably higher in green wheat (0.16%) compared to mature yellow wheat (0.07%), while fructose and glucose were undetectable in the mature wheat. This higher sugar content in premature green wheat likely correlates and contributes to its sweeter taste, potentially enhancing its flavor profile (Yang et al. 2012).

Freekeh is also abundant in oligosaccharides, particularly fructo-oligosaccharides (FOS), which are becoming increasingly recognized for their nutritional significance. FOS in Freekeh consists of branched molecules with both β-2-1 and β-2–6 fructosyl-fructose linkages that have a low degree of polymerization (Casiraghi et al. 2013). Large quantities of FOS accumulate in the stems and grains throughout much of the wheat's growing cycle, peaking during the milky phase before rapidly declining. Harvesting wheat at this stage maximizes the FOS content while keeping starch levels low, making Freekeh an excellent candidate for functional food applications (Iametti et al. 2006). The elevated FOS content in Freekeh provides health benefits not typically found in mature wheat (Bayram 2008; Zhang et al. 2021a). As non-digestible fructose polymers, FOS resist enzymatic digestion and undergo fermentation in the colon, producing short-chain fatty acids (SCFAs), which serve as an energy source for colon cells. Both FOS and SCFAs contribute to gut health by promoting the growth of beneficial Bifidobacteria. Research suggests that a daily intake of 10 grams of FOS is sufficient to stimulate Bifidobacteria proliferation, supporting digestive health and overall well-being (Wierdsma et al. 2009). However, while FOS offer health benefits, they can cause bloating, gas, and diarrhea, particularly in individuals with IBS. In addition, in FODMAPs, the FOS may exacerbate digestive symptoms by promoting rapid fermentation and drawing excess water into the intestines.

6.2. Proteins

Wheat proteins are primarily classified into soluble proteins (albumins and globulins) and storage proteins (gliadins and glutenin). These proteins play crucial roles in wheat grains and food products, particularly in bread making, and their physicochemical properties have been extensively documented (Delcour and Hoseney 2010).

Freekeh contains about 13.9% protein which is similar or slightly higher than mature wheat (~11%–13% protein), but the types and quantities of proteins vary depending on the harvest time (Özkaya et al. 2018). The synthesis and accumulation of individual proteins in developing wheat grains occur at different times and rates, making the protein composition highly dependent on the grain's maturity stage. Research has shown that there are only marginal differences in nitrogen content between mature grains and kernels at the milky stage, which occurs between the second and third week after anthesis (Iametti et al. 2006; Özboy et al. 2001; Özkaya et al. 2018; Yang et al. 2012). During this milky phase, albumins and globulins are the predominant proteins, while proteins responsible for gluten network formation are absent. The specific types of albumins and globulins present change over the first three weeks after anthesis, but their pattern stabilizes from the fourth week through to maturity. Gliadins are detectable in kernels as early as 10 DAA, and both high-molecular-weight glutenin subunits (HMW-GS) and low-molecular-weight glutenin subunits (LMW-GS) appear by 13 DAA. The production and accumulation of these proteins continue until the grains reach physiological maturity (Iametti et al. 2006).

Freekeh offers several nutritional advantages, particularly in terms of protein quality, including its digestibility, amino acid composition, and biological value, making it a superior choice compared to mature wheat. According to Yang et al. (2012), Freekeh has significantly higher levels of essential amino acids, such as lysine, methionine, isoleucine, valine, and threonine compared to mature yellow wheat. These essential amino acids are crucial because the body cannot synthesize them and must obtain them through diet. Furthermore, the amino acid score (AAS) for these essential amino acids including lysine (69), valine (138), isoleucine (133), and threonine (96) in Freekeh were notably higher than that of mature wheat, underscoring its superior protein quality (Yang et al. 2012). The values for amino acids scores can vary due to variations in wheat varieties and crop years (Anjum et al. 2005).

In terms of protein digestibility, Zhang et al. (2020) found that Freekeh protein behaves differently in the digestive process compared to mature wheat. During the initial gastric stage, Freekeh protein exhibits lower digestibility, likely due to its immaturity and the incomplete development of certain proteins. However, as the digestion progresses, Freekeh's protein digestibility increases, eventually reaching levels comparable to or slightly higher than mature wheat. This improvement in later stages of digestion may be attributed to the low glutenin content in Freekeh, which is easier to break down, as well as its higher fiber content, which could play a role in regulating protein digestion (Zhang et al. 2020).

Overall, the protein bioavailability of Freekeh remains high across the digestive process, with its biological value enhanced by the superior amino acid profile. The high AAS of essential amino acids like valine and histidine in Freekeh, combined with its efficient digestion and absorption, make it a nutritionally valuable protein source. These characteristics position Freekeh as a functional food with potential benefits for improving dietary protein intake, particularly in diets where cereal grains are a primary protein source (Yang et al. 2012; Zhang et al. 2020).

6.3. Lipids

The fat content of Freekeh typically ranges between 1.32% and 2.70%, while mature wheat contains 2.1%–3.3% of lipid content, which contributes to its overall nutritional profile (Majzoobi et al. 2023; Waters et al. 2012). It has been reported that Freekeh contains 1.50% linoleic acid, which is higher than the 1.29% found in mature yellow wheat. The study further indicated that Freekeh exhibited significantly higher levels of key fatty acids such as palmitic, oleic, and linoleic acids compared to mature yellow wheat ($p < 0.05$). Among these, linoleic acid emerged as the major fatty acid, comprising 56.39%–58.37% of the total fatty acid content in both Freekeh and mature wheat samples (Yang et al. 2012).

In a related study, Cutignano and colleagues characterized the lipid fraction in the developing grain of durum wheat (*Triticum turgidum ssp. durum* (Desf.) Husn), specifically the Svevo cultivar, to track lipid evolution throughout grain maturation. They analyzed triacylglycerols (TAGs) and methylated free fatty acids (FFAs) at five critical stages of kernel development, spanning from 5 to 30 days post anthesis (dpa). The study revealed the early presence of TAGs, at low concentrations, with a subsequent accumulation of linoleate (C18:2n6)-rich C52 and C54 TAGs as the kernel filling progressed. Moreover, the fatty acid composition of polar lipids, including phospholipids and galactolipids, showed a dominance of linoleate from two weeks post anthesis. In contrast, sphingolipids such as ceramides and glucosylceramides, which consisted mainly of saturated long-chain fatty acids, were likely involved in signaling roles during grain development (Cutignano et al. 2021).

Merendino and colleagues studied the impact of immature versus mature durum wheat (cultivar Simeto) on lipid profiles in growing rats. Wheat samples were collected at 15 and 45 DAA and incorporated into diets containing 53% of the whole meals. Rats fed with immature wheat showed significantly reduced plasma triglycerides and cholesterol levels compared to those fed on mature wheat diets, indicating a beneficial effect on lipid profiles (Merendino et al. 2006).

6.4. Ash and minerals

Ash content provides an estimate of the total mineral content in food, offering insight into its nutritional value. Several studies have examined the ash content of Freekeh from different wheat cultivars, revealing important trends in its mineral composition. Özboy and colleagues investigated two durum wheat varieties, Duraking and Ege 88, across five maturation stages, finding that the ash content of Freekeh decreased significantly as the wheat matured. Notably, Freekeh prepared by roasting had a higher ash content than the boiled version, likely due to mineral loss during boiling (Özboy et al. 2001). Similarly, Özkaya et al. (2018) studied three wheat varieties, two Hard Red Winter wheats (C-1252 and Bezostaya) and one durum wheat (Eser), across four maturation stages. Their findings also showed a significant reduction in ash content as wheat matured, with the Cesit-1252 cultivar exhibiting the largest decline of around 40%. Both studies emphasize the consistent trend of ash content reduction with maturation and highlight how cooking methods and wheat variety can influence the final ash content in Freekeh (Özkaya et al. 2018).

Among the macro minerals, Freekeh is particularly high in potassium (369–451 mg/100 g), magnesium (160–202 mg/100 g), and phosphorus (412 mg/100 g). Potassium helps regulate fluid balance, muscle contractions, and nerve signals, while magnesium is essential for bone health and cartilage formation. Phosphorus contributes to bone and teeth strength, energy production, and cellular function. In addition, Freekeh contains significant amounts of micro minerals like iron (5.02 mg/100 g) and zinc (3.98 mg/100 g). Iron is crucial for preventing anemia and maintaining vitality, while zinc supports immune function, skin health, and reproductive health. This mineral-rich profile underscores Freekeh's value as a nutritious food that offers a wide range of health benefits throughout various stages of life (Majzoobi et al. 2023; Saini et al. 2021).

6.5. Bioactive compounds

Freekeh is a rich source of bioactive compounds, containing nearly twice the total phenolic and flavonoid content, as well as higher antioxidant properties compared to mature wheat. Key bioactive compounds in Freekeh include ferulic acid, lutein, zeaxanthin, and vitamins C, B1, B2, B3, and E (Majzoobi et al. 2023; Yang et al. 2012; Zhang et al. 2020; Zhang and Zhang 2019).

Recent studies have provided valuable insights into the health benefits of immature wheat compared to mature wheat, particularly in terms of antioxidant capacity and antiproliferative activity. Kim, Yoon, and Kim (2016) investigated the phytochemical composition and bioactivity of immature wheat bran (IWB) and found that it contained significantly higher levels of ferulic acid (3.09 mg/g) and *p*-coumaric acid (0.075 mg/g) compared to mature wheat bran (MWB). The IWB exhibited enhanced antioxidant properties, with higher oxygen radical absorbance capacity (ORAC) and cellular antioxidant activity (CAA) values. Furthermore, IWB extracts demonstrated potent antiproliferative effects, as evidenced by the lowest EC_{50} values against HT-29, Caco-2, and HeLa cells, alongside an increase in the expression of the tumor suppressor genes p53 and PTEN in HT-29 cells, suggesting its potential for cancer prevention (Kim, Yoon, and Kim 2016). In a related study by Kim and Kim (2016), immature wheat (harvested 35 DAA) also showed higher antioxidant contents, including higher total phenolic (5.32 mg GAE/g) and flavonoid (4.73 mg CE/g) levels, compared to mature wheat. Despite the lower vitamin E content in immature wheat (4.02 mg/100g), its antioxidant capacity, measured by ORAC, was notably higher. Immature wheat extracts further demonstrated strong antiproliferative activity against HT-29 and HeLa cells, as evidenced by the lowest EC_{50} values, further supporting its potential as a functional food ingredient with cancer-fighting properties (Kim and Kim 2016).

Özkaya et al. (2018) investigated the nutritional composition of three wheat varieties; Two Hard Red Winter wheats (C-1252 and Bezostaya) and one durum wheat (Eser) at four different maturation stages. Their findings also revealed that immature wheat, particularly in the early stages of kernel development, is significantly higher in total phenolic content (TPC) with a range from 4.60 to 4.83 mg GAE/g, while antioxidants were measured between 7.29 and 7.82 µmol TE/g. In contrast, mature wheat exhibited lower values, with TPC ranging from 1.90 to 2.23 mg GAE/g and antioxidants from 4.12 to 4.67 µmol TE/g (Özkaya et al. 2018).

In another study, Zhang et al. (2023) examined the phenolic content in immature wheat (Freekeh) at 15, 30, and 45 DAA. The study found a decrease in total phenolic content (TPC) with maturity, from 504.80 mg GAE/100 g DW in DAA-15 wheat flour to 233.83 mg GAE/100 g DW in DAA-45. Insoluble-bound phenolics (IBPC) were the dominant form, contributing up to 64.85% of TPC in DAA-30. The findings suggest that earlier maturity stages, especially DAA-15, offer a higher phenolic content, making Freekeh a rich source of bioactive compounds compared to mature wheat (Zhang et al. 2023).

Ferulic acid (FA), a major phenolic compound in Freekeh, is known for its potent antioxidant properties, helping to combat oxidative stress linked to chronic diseases such as cancer, diabetes, and neurodegenerative disorders. Additionally, FA exhibits antimicrobial, anti-inflammatory, and anticancer effects, supporting overall cellular and tissue health (de Oliveira Silva and Batista 2017).

Chlorophyll is another bioactive compound in Freekeh offering several health benefits, including antioxidant and anti-inflammatory properties that help reduce oxidative stress and lower the risk of chronic diseases. It supports liver detoxification by aiding in the removal of toxins and heavy metals, while also promoting red blood cell production and improving oxygen transport. Chlorophyll enhances gut health by balancing gut bacteria and reducing bad breath, and it may also provide anti-cancer benefits by blocking carcinogen absorption. Additionally, it supports wound healing, skin health, and weight management by reducing appetite (Zhang et al. 2021b).

Vitamins are another group of bioactive compounds in Freekeh that contribute to its superior nutritional profile. Compared to mature yellow wheat, green wheat harvested for Freekeh contains significantly higher levels of B vitamins, including niacin (1.30 mg/100 g vs. 0.06 mg/100 g) and riboflavin (0.19 mg/100 g vs. 0.06 mg/100 g), both essential for energy metabolism and cognitive function. Thiamin (vitamin B1), which plays a key role in carbohydrate metabolism, supporting nerve function and preventing fatigue, while riboflavin (vitamin B2) aids in macronutrient metabolism, helping to prevent anemia and muscle weakness. Niacin (vitamin B3) is particularly important for DNA repair, brain health, and cognitive function, with deficiencies linked to memory loss and depression (Yang et al. 2012). Freekeh contains about (4.0–4.5 mg/100 g) of vitamin C, an essential antioxidant that supports immune function and protects cells, whereas mature wheat has no detectable levels of this vitamin (Yang et al. 2012). Conversely, mature wheat is richer in α-tocopherol (vitamin E) at 1.31 mg/100 g, compared to 0.60 mg/100 g in green wheat, enhancing its antioxidant potential. Vitamin E plays a crucial role in protecting cells from oxidative damage, strengthening immune function, and maintaining cellular integrity (Kim and Kim 2016; Yang et al. 2012). All up, the vitamin profile of Freekeh enhances metabolic health, protects against oxidative stress, and supports overall well-being (Tardy et al. 2020).

Freekeh also contains carotenoids (precursor for vitamin A), which further enhances its nutritional value compared to mature wheat. It has been reported that Australian Freekeh has significantly higher concentrations of lutein (0.079 mg/100g) and zeaxanthin (0.032 mg/100g) compared to North American wheat varieties such as Catoctin and Pioneer. However, the levels of lutein and zeaxanthin in Freekeh are much lower than those found in fruits and vegetables. Green vegetables such as kale (lutein – 0.24 mg/100g; zeaxanthin – 15.00 mg/100g), spinach (lutein – 9.15 mg/100g; zeaxanthin – 0.53 mg/100g), parsley (lutein – 0.52 mg/100g; zeaxanthin – 10.82 mg/100g), and yellow orange vegetables such as butternut squash (lutein – 0.280 mg/100g; zeaxanthin – 2.40 mg/100g) contain higher concentrations of these carotenoids compared to Freekeh (Humphries and Khachik 2003). These carotenoids act as potent antioxidants and precursors to vitamin A, playing a crucial role in eye health and reducing the risk of age-related macular degeneration (Humphries and Khachik 2003). This unique combination of vitamins and carotenoids underscores Freekeh's potential as a functional food with significant health benefits.

Processing techniques such as roasting and steaming play a key role in influencing the bioactive compound composition of immature wheat grains. Several studies have examined how thermal processing methods like boiling and roasting affect the phenolic content and bioaccessibility of highland barley (HB). Results showed that both treatments increased the extractability of free and bound phenolics, as well as antioxidant activity, likely due to the disruption in the grain matrix. *In vitro* digestion further revealed that thermal processing significantly enhanced phenolic bioaccessibility compared to raw HB, with boiled samples showing the highest bioaccessibility (36.3%), followed by roasted samples (22.75%) (Hong et al. 2023; Wang et al. 2022).

Similarly, the impact of roasting whole wheat flours at 80 °C, 100 °C, and 120 °C for 30 min was evaluated across different developmental stages (15, 30, and 45 days) after anthesis (DAA) in relation to four forms of phenolics, Maillard reaction products (MRPs), and DPPH scavenging activity (DSA). Roasting enhanced both phenolic content and antioxidant activity, mainly through MRP formation. The highest total phenolic content (TPC) and total phenolic DSA (TDSA) were observed in 15-DAA flours roasted at 120 °C, indicating that early-stage wheat and higher roasting temperatures provide stronger antioxidant properties (Zhang et al. 2023). Thus, roasting, commonly used in Freekeh production, can improve phenolic availability and antioxidant properties by modifying the grain structure.

However, prolonged or high-temperature roasting may degrade heat-sensitive nutrients such as tocopherols and flavonoids. In one study, wheat germ dried at 80 °C, 90 °C, and 100 °C for 75 min showed significant reductions in bioactive compounds: lutein decreased by 37.24%–49.22%, total phenolics by 41.41%–43.67%, and antioxidant activity by 31.25%–45.70% (Çulluk, Demiray, and Çalışkan Koç 2025). Another study evaluating roasting at 150 °C and 180 °C for 20 min on whole cowpea (*Vigna unguiculata*) pulses, found significant ($p < 0.05$) decreases or complete loss of flavonoids and phenolic acids, including gallic acid, catechin, caffeic acid, quercitrin, kaempferol, and apigenin, likely due to heat-induced oxidation and thermal breakdown (Irondi et al. 2019).

In contrast, steaming is a milder process that better preserves bioactive components. Studies have shown that steaming retains higher levels of phenolics, and antioxidant activity compared to roasting (Hong et al. 2023). Therefore, careful control of processing conditions is essential to maintain the nutritional quality of Freekeh.

7. Allergenicity, intolerance, and antinutrients

There is a paucity of research specifically addressing the allergenicity and intolerance of Freekeh. However, an examination of existing studies and literature pertaining to the allergenicity of common wheat reveals that various components of wheat are responsible for eliciting immune responses and gastrointestinal symptoms in certain individuals. The diversity in wheat's protein composition and the different pathways through which these proteins affect susceptible individuals underscore the complexity of wheat allergenicity. Given that Freekeh is derived from wheat harvested while still green, it is plausible that it shares similar allergenic properties, though further empirical studies are required to confirm this hypothesis. Understanding the specific allergenic potential of Freekeh is essential for providing accurate dietary recommendations for individuals with wheat-related disorders.

7.1. Freekeh allergenicity

Prolamins make up 80% of all wheat proteins, including α/β-, α-, and ω5-gliadins, as well as low- and high-molecular-weight glutenin subunits, and are regarded as the primary allergens responsible for wheat allergies. Additionally, wheat proteins in the water/salt-soluble fraction, mainly consisting of α-amylase/trypsin inhibitors, peroxidase, thioredoxin, serpin, and nonspecific lipid transfer proteins, were identified as major allergens in individuals with urticaria, baker's asthma, and atopic dermatitis (Brouns et al. 2019; Liu et al. 2023; Zhao et al. 2021).

During the milky phase, albumins and globulins are the predominant protein components, while proteins essential for gluten network formation are lower. Although the types of albumins and globulins change during the first three weeks after anthesis, their overall levels remain stable from week 4 until maturity. Gliadins can be detected in kernels as early as 10 DAA, with both high-molecular-weight glutenin subunits (HMW-GS) and low-molecular-weight glutenin subunits (LMW-GS) appearing by 13 DAA (Johansson et al. 1994; Molino et al. 1988). Iametti et al. (2006) studied the Ofanto and Duilio durum wheat cultivars grown in experimental fields in Rome, Italy, with grains harvested at various stages from 9 to 28 DAA. Using immunoblotting with anti-gliadin antibodies, they observed that the gluten polypeptide synthesis differed between the cultivars. Gliadin synthesis in Ofanto began at 17 DAA, with no immunoreactive proteins present earlier, while Duilio showed detectable levels by 15 DAA, indicating earlier gluten protein production. These findings suggest that grains harvested during the milky phase, lacking gliadins but rich in proteins with suitable processing properties, may serve as promising raw materials for gluten-sensitive food products (Iametti et al. 2006).

7.2. Wheat intolerance

Celiac disease (CD) represents the most significant wheat-related intolerance. It is an autoimmune disorder triggered by gluten, specifically the highly immunogenic α-gliadin peptides. In genetically predisposed individuals expressing HLA-DQ2 or HLA-DQ8 molecules, gluten ingestion leads to T-cell-mediated immune responses that cause intestinal inflammation, villous atrophy, and mucosal damage (Liu et al. 2023). This disease is characterized by gastrointestinal symptoms such as diarrhea, malabsorption, and weight loss, but it can also manifest as extra-intestinal symptoms, including dermatitis herpetiformis and anemia. Non-celiac gluten sensitivity (NCGS) is another wheat-related disorder where individuals experience gastrointestinal and non-gastrointestinal symptoms, including fatigue and headaches, which are resolved upon gluten withdrawal. However, unlike CD, NCGS does not involve the characteristic intestinal damage seen in celiac patients (Brouns et al. 2019; Sharma et al. 2020).

Zhang et al. (2022) investigated the immunogenic potential of green wheat protein by analyzing its peptide composition post-digestion. Using green wheat (Bainong 201), the study employed LC-MS to characterize the peptides generated from simulated digestion in the stomach and intestine. The findings revealed the presence of immunogenic peptides linked to celiac disease after digestion with pepsin and trypsin. This highlights potential concerns regarding the consumption of green wheat in individuals with celiac disease and underscores the importance of further research to assess the clinical implications and safety of green wheat protein in susceptible populations (Zhang et al. 2022).

7.3. Freekeh indigestion

Dietary intake of fermentable oligo-, di-, and monosaccharides, and polyols (FODMAPs) have been shown to exacerbate symptoms of irritable bowel syndrome (IBS). Additionally, there is evidence linking FODMAPs with wheat sensitivity and specific intolerance to wheat. This suggests that individuals with IBS or wheat intolerance may benefit from monitoring and potentially reducing their consumption of FODMAP-containing foods (Altobelli et al. 2017; Liu et al. 2023; Tuck et al. 2014). Immature wheat grains (IWG) contain fewer FODMAPs and have a lower starch content, making them less prone to enzymatic digestion and possibly less likely to trigger these symptoms (Carsiraghi et al. 2006).

7.4. Freekeh antinutrients

Phytic acid, a known antinutrient in cereals, including wheat, is of particular concern due to its ability to chelate essential minerals such as calcium, zinc, and iron, making them less bioavailable to humans and monogastric animals (Bayram 2008). Özboy and colleagues investigated two durum wheat cultivars, Duraking and Ege 88, at different maturation stages (13, 16, 19, 22, and 25 days post-anthesis). These varieties were processed into Freekeh using two cooking methods: flame roasting and boiling under atmospheric pressure. At 13 days post-anthesis, roasted Freekeh from Duraking and Ege 88 contained lower phytic acid content (~678 and 699 mg/100 g) compared to 833 and 890 mg/100 g in their mature wheat counterparts. The study also found that total phosphorus (P) levels in Freekeh decreased significantly as maturation progressed, while phytic acid levels increased, regardless of the cooking method used (Özboy et al. 2001).

In another study, Özkaya et al. (2018) analyzed the total phosphorus (P), phytic acid, and phytate P content in three wheat varieties two Hard Red Winter wheats (C-1252 and Bezostaya) and one durum wheat (Eser) at four maturation stages (10, 15, 20, and 25 DAA) and in matured grains. Their findings showed that while the phytic acid content in Freekeh increased significantly throughout maturation, the total phosphorus levels declined across all cultivars. This decrease in the total P, especially after the second week post-anthesis, corresponded with its conversion into phytic acid. The most rapid rise in phytic acid occurred during early maturation, nearly doubling by full maturity. Similarly, phytate P content showed a consistent upward trend in all wheat varieties (Özkaya et al. 2018).

Phytase, the enzyme responsible for breaking down phytic acid, undergoes changes throughout wheat maturation. In its early stages, immature wheat exhibits higher phytase activity, which aids in phosphate mobilization to support rapid growth and development. As the grain matures, phytase activity gradually declines, leading to the accumulation of phytic acid in the aleurone layer and embryo. This enzyme plays a vital role during germination, breaking down stored phytic acid to release phosphorus essential for seedling growth. Additionally, environmental factors such as temperature and drought stress can impact phytase activity, potentially influencing phytic acid degradation and the bioavailability of minerals in wheat-based foods (Reddy, Sathe, and Salunkhe 1982).

The reduction in phytic acid correlates with an increase in mineral availability, particularly for calcium, zinc, and iron, which is beneficial for individuals who rely heavily on cereals for their nutrient intake (Özboy et al. 2001).

8. Food applications of Freekeh

Fresh and dried or roasted Freekeh serve as a primary raw material in the production of various traditional and modern foods and nutritious as shown in Figure 5. Roasted Freekeh, a traditional staple, has enjoyed popularity in the Middle Eastern, North African, and Chinese cuisines for centuries. Freekeh holds a status akin to rice, bulgur, and couscous as a staple food. Its ground or chopped grains are typically boiled or steamed and served alongside sheep or poultry meat (Bayram 2008). Fresh green Freekeh can also be cooked with meat, resembling the preparation of rice or bulgur in a pilaf. In Syria, it is often utilized to stuff various vegetables such as squash, eggplant, and grape leaves, or simmered in chicken broth (Musselman and Al-Mouslem 2001). Additionally, Freekeh pilaf is a cherished traditional dish across Anatolia and Middle Eastern countries, typically featuring Freekeh cooked with meat, tomatoes, salt, and fats such as butter or oil (Özkaya et al. 1999).

While the food applications of Freekeh have historically been confined to certain traditional and homemade dishes, the growing awareness of its nutritional and health advantages suggests a potential rise in global consumption and applications in the modern food industry. Several studies have begun to explore the utilization of Freekeh in the development of healthy foods. For instance, research indicates that incorporating Freekeh flour into noodle formulations can improve the quality of the noodles and lower their predicted GI. This suggests promising prospects for expanding the use of green wheat in diverse food products aimed at promoting health and wellness (Zhang et al. 2021b).

Freekeh is a valuable source of plant-based protein and can be used to enhance the nutritional profile of various plant-based products. While its total protein content remains comparable to wheat at the late ripening stage, Freekeh is rich in albumins, which offer a well-balanced amino acid composition, and contains lower levels of gliadins (Casiraghi et al. 2011; Iametti et al. 2006). Since the gluten-forming proteins are present in reduced amounts, Freekeh can be blended with conventional wheat flour or semolina to improve protein content in staple foods such as pasta, bread, and biscuits. Alternatively, it can be directly incorporated into soups or baby foods. Previous studies have shown that adding up to 30% immature wheat grains to the whole-meal mixture is the maximum level feasible within the parameters of a conventional pasta-making process (Casiraghi et al. 2013). Furthermore, recent *in vitro* findings support the potential of immature wheat grains as a prebiotic ingredient. Additionally, *in vivo* data indicates that biscuits enriched with immature wheat grains may impact gastric emptying and contribute to satiety (Casiraghi et al. 2011, 2013).

Demirci et al. (2019) investigated the effects of incorporating Freekeh or immature wheat grain flour into yoghurt. The research focuses on the survival of three probiotic strains *Lactobacillus acidophilus* NCFM (LNCFM), *Lactobacillus casei* 431 (L431), and *Lactobacillus acidophilus* 20079 (L20079) during cold storage. The findings indicated that Freekeh fortification significantly enhanced the survival of LNCFM and L20079, but not L431. Additionally, Freekeh improved the antioxidative activity and total phenolic content of the yoghurt, although it did not affect syneresis or water holding capacity. Texturally, Freekeh increased the firmness of the yoghurt but decreased its cohesiveness and viscosity. The study concluded that Freekeh can be a beneficial additive for improving the functional properties and probiotic viability in yoghurt (Demirci et al. 2019).

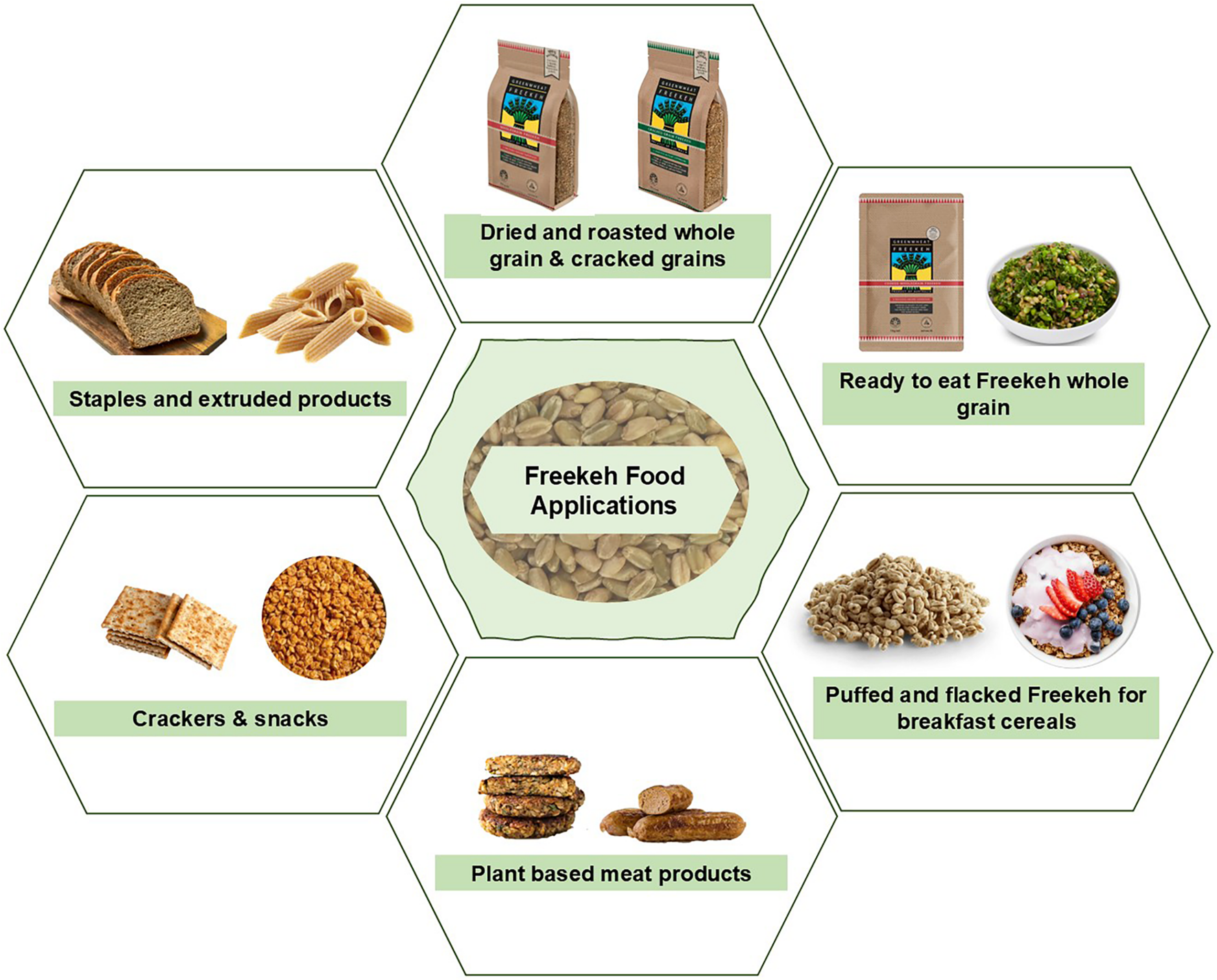

Figure 5. Various food applications of Freekeh.

Pepe et al. (2013) showed that incorporating 20% Freekeh flour, dextran-producing lactic acid bacteria strains, and using a sourdough process enhanced the metabolism of lactic acid bacteria and yeast, resulting in reduced leavening times and increased exopolysaccharide production in dough. This approach enabled the creation of prebiotic bread that meets approximately 30% of the daily fructo-oligosaccharides requirement, thereby augmenting the daily intake of prebiotics (Pepe et al. 2013).

As the nutritional benefits of Freekeh become more evident, its applications in various food products are expanding, offering promising opportunities to increase its global consumption. This shift not only diversifies culinary practices but also enhances the overall health and wellness of consumers.

9. Advantages and disadvantages of Freekeh as compared to other emerging grains

9.1. Proximate composition

Freekeh is a nutrient dense grain with a well-balanced composition of protein, starch, dietary fiber, and minerals (Table 1). Its protein content ranges from 11–15%, which is comparable to quinoa (12%–23%) and wild rice (10%–15.5%), but is higher than colored rice (6.5%). The starch content in Freekeh (45%–68%) is lower than colored rice (85%–90%) and wild rice (56%–79%). It is a rich source of dietary fiber (12%–19%), surpassing quinoa (2%–2.2%), colored rice (4.95%–6.76%), and wild rice (6.8%). Regarding minerals, green wheat stands out by possessing high potassium (369–451 mg/100g), magnesium (160–202 mg/100g), and phosphorus (412 mg/100g) levels, comparable to or exceeding the values in other grains. Its calcium content (32–63 mg/100g) is similar to quinoa (32.9 mg/100g) but higher than wild rice (21–24 mg/100g). Overall, Freekeh emerges as a nutritionally balanced grain with an impressive mineral profile and fiber content.

9.2. Bioactive compounds, vitamins, antioxidants and antinutrients

Freekeh stands out for its remarkably high ferulic acid content at 309 mg/100 g, far exceeding the levels found in quinoa (0.251 mg/100g), colored rice (up to 25.28 mg/100g), wild rice (up to 35.5 mg/100g), and chia seeds. It is also a good source of antioxidants including lutein (0.079 mg/100g) and zeaxanthin (0.032 mg/100g). For vitamins, green wheat

Table 2. Bioactive compounds, vitamin, and antinutrient content of Freekeh, mature wheat and other emerging grains.

Grain Type	Bioactive compounds	Vitamins	Antinutrients & Toxic compounds	References
Freekeh	TPC: 460–532 g GAE/100 g TFC: 475 mg CE/100 g Ferulic acid: 309 mg/100 g p-coumaric acid (7.50 mg/100 g) Sinapic acid: (10.70 mg/100 g) Vanillic acid: (6.37 mg/100 g) Syringic acid: (21.64 mg/100 g) Caffeic acid: (1.16 mg/100 g) Lutein: 0.079 mg/100 g Zeaxanthin 0.032 mg/100 g	Vit. B1: 1.80 mg/100 g Vit. B2: 0.19 mg/100 g Vit. B3: 1.30 mg/100 g Vit. B6 0.07 mg/100 g Vit B9: 0.08 mg/100 g Vit. C: 4.5 mg/100 g Vit. E (α – Tocopherol):0.60 mg/100 g	Phytic acid 660–700 mg/100 g	(Abdel-Aal et al. 2013; Humphries and Khachik 2003; Kim, Yoon, and Kim 2016; Kim and Kim 2016; Özboy et al. 2001)
Mature Wheat	TPC: 190–446 g GAE/100 g TFC: 234 mg CE/100 g Ferulic acid: 179 mg/100 g p-coumaric acid (5.52 mg/100 g) Sinapic acid: (12.10 mg/100 g) Vanillic acid: (7.45 mg/100 g) Syringic acid: (29.50 mg/100 g) Caffeic acid: (1.03 mg/100 g)	Vit. B1: 1.41 mg/100 g Vit. B2: 0.06 mg/100 g Vit. B3: 0.06 mg/100 g Vit. B6 0.16 mg/100 g Vit. C: not detected Vit. E (α – Tocopherol): 1.31 mg/100 g	Phytic acid: 830–890 mg/100 g	(Kim, Yoon, and Kim 2016; Kim and Kim 2016; Vaher et al. 2010; Yang et al. 2012)
Quinoa	Ferulic acid: 0.251 mg/100 g *p*-coumaric acid 1.1 μg/g Caffeic acid: 6.31 μg/g	Vit B1: 0.38 mg/100 g Vit B2: 0.39 mg/100 g Vit B3: 0.5–0.7 mg/100 g Vit B6: 0.49 mg/100 g Vit B9: 0.08 mg/100 g Vit E: 5.37 mg/100 g Vit A: 14 mg/ 100 g	Phytic acid: 1050–1310 mg/100 g Saponins: 1000–6000 mg/100 g	(Angeli et al. 2020; Satheesh and Fanta 2018)
Colored Rice	TPC: 118.47–579 mg/100 g Anthocyanin content (mg cyanidin-3-glucoside equivalent 100^{-1} g): 0.35–6.52. Carotene: 4.95–9.65 μg/g. Gallic acid: 0.23–6.44 mg/100 g Caffeic acid: 2.78–25.28 mg/100 g.	Vit B2: 0.06 mg/100 g Vit B3: 1.92 mg/100 g Vit E: 1.20 mg/100 g	Not reported	(Aini, Dwiyanti, and Salamah 2023; Rathna Priya et al. 2019; Satheesh and Fanta 2018)
Wild rice	TPC: 16.98–58.8 mg/100 g Ferulic acid: 24.1–35.5 mg/100 g Sinapic acid: 5.5–9.6 mg/100 g *p*-coumaric acid: 1.1–4.3 mg/100 g	Vit. B1: 0.30–0.63 mg/100 g Vit. B2: 0.07–0.2 mg/100 g Vit. E: 0.2–4.8 mg/100 g	Not reported	(Majzoobi et al. 2023)
Chia seeds	Caffeic acid: 27 μg/g Quercetin: 0.17 μg/g Kaempferol: 0.013 μg/g	Vit. B2: 0.17 mg/100 g Vit. B3: 8.83 mg/100 g Vit. B1: 0.62 mg/100 g Vit. E: 8.1 mg/100 g Vit. C: 1.6 mg/100 g	Phytic acid; 960 and 1160 g/100 g	(Hrnčič et al. 2019; Kulczyński et al. 2019)

TPC: Total Phenolic Content; TFC: Total Flavonoid Content.

provides higher amounts of B1, B3, and C compared to quinoa, colored rice, and chia seeds. However, it contains substantially a greater phytic acid content (Table 2).

The high levels of ferulic acid, lutein, and zeaxanthin in green wheat contribute to its potent antioxidant and anti-inflammatory properties, which can potentially reduce the risk of various chronic diseases, including cancer, diabetes, cardiovascular diseases, and age-related eye disorders.

9.3. Essential and non-essential amino acids

Essential amino acids are crucial and must be obtained through dietary sources since the human body cannot produce them. Among these, lysine and threonine are particularly deficient (Anjum et al. 2005). The functional characteristics of wheat protein are additionally impacted by nonessential amino acids, which play a role in gluten development (Peña et al. 2005).

Freekeh is distinguished for its significantly higher levels of lysine, methionine, isoleucine, valine, and threonine compared to mature yellow wheat. Freekeh offers a well-balanced amino acid profile in comparison to other grains such as quinoa, colored rice, wild rice, and chia seeds (Table 3). Freekeh also contains significant amounts of lysine (4.0 g/100 g) and threonine (3.3 g/100 g) which are often limited in cereal grains. Regarding non-essential amino acids, Freekeh is prominent for high levels of glutamic acid and proline. These non-essential amino acids influence the quality of wheat proteins (Yang et al. 2012).

Freekeh and quinoa share some similarities in their amino acid profiles, with comparable levels of lysine, threonine, arginine, aspartic acid, and glycine. However, Freekeh is notable for its higher amounts of the essential amino acid leucine, isoleucine, and valine (Angeli et al. 2020; Yang et al. 2012). The amino acid profile of Freekeh is significantly more balanced and abundant compared to wild rice, colored rice, and Chia seeds. Freekeh contains substantially higher amounts of most essential amino acids, such as valine, isoleucine, leucine, and lysine (Kulczyński et al. 2019; Santos et al. 2013; Zhu et al. 2024). Overall, it highlights that Freekeh is a more complete and balanced plant-based protein source, making it a valuable addition to a well-rounded diet.

Table 3. Comparison of amino acid content of Freekeh, mature wheat and other emerging grains.

Amino acids (g per 100 g crude protein)	Freekeh	Grain Type				
		Mature wheat	Quinoa	Colored Rice	Wild rice	Chia seeds
			Essential amino acids			
Valine	4.8	4.5	5.7	0.7–1.8	0.7	0.8
Methionine	1.6	1.4	1.8	0.08–0.2	0.2	0.7
Isoleucine	3.7	3.5	2.8	1.7–3.3	0.5	0.7
Leucine	7.3	7.4	5.3	0.2–0.6	1.0	1.4
Threonine	3.3	2.9	3.2	0.7–1.9	0.5	0.5
Phenylalanine	4.1	4.9	3.2	1.0–1.2	0.7	1.6
Lysine	4.0	2.8	4.9	0.8–1.6	0.4	0.9
Histidine	2.1	2.3	2.3	0.8–2.0	0.3	0.6
Tryptophan	NA	NA	1.0	1.3–4.5	0.11	n/d
			Nonessential amino acids			
Arginine	4.0	4.3	6.6	1.5–3.9	0.9	2.0
Aspartic acid	5.8	4.9	6.0	8.0–16.8	1.1	1.3
Tyrosine	1.7	1.7	2.3	0.5–0.1	0.6	0.6
Serine	5.3	4.9	3.3	2.7–4.2	0.6	0.9
Glutamic acid	28.5	33.9	8.5	5.3–22.7	2.2	2.8
Proline	8.3	10.6	3.2	1.0–2.2	0.5	1.2
Glycine	4.6	4.2	4.6	–	0.5	0.9
Alanine	5.7	3.7	3.3	3.0–6.1	0.6	0.9
Cystine	0.9	1.2	1.4	–	0.3	0.42
References	(Yang et al. 2012)	(Yang et al. 2012)	(Angeli et al. 2020)	(Zhu et al. 2024)	(Santos et al. 2013)	(Kulczyński et al. 2019)

10. Conclusion and future prospectives

Freekeh, an ancient wheat-based cereal, demonstrates significant promise as a sustainable and nutrient-dense grain suitable for modern dietary needs. Its high content of dietary fiber, essential minerals, and antioxidants positions it as a strong alternative to other whole grains such as quinoa and wild rice. Coupled with its eco-efficient production methods, Freekeh aligns with global goals for sustainable agriculture and health-focused food systems. However, its wheat origin raises potential allergenicity concerns, and current data on its detailed nutritional components—particularly fiber types, fatty acid profiles, and bioactive compounds, remain limited. In addition, more research is needed on consumer acceptance, functional properties in food applications, and optimized agronomic practices. Addressing these gaps through multidisciplinary research will be critical for unlocking Freekeh's full potential in health promotion, product development, and global food sustainability initiatives.

Despite Freekeh's nutritional and functional potential, several research gaps remain. Agronomic studies tailored to Freekeh are limited; optimizing cultivation practices such as harvest timing and varietal selection could enhance yield and quality. Nutritional analyses have primarily focused on basic composition; detailed investigations into its soluble and insoluble fiber fractions, fatty acid profiles, and bioactive compounds are necessary to fully understand its health benefits. Industrial applications of Freekeh are underexplored; research into its functional properties in various food processing methods could facilitate its incorporation into diverse products. Consumer acceptance studies are scarce; understanding sensory preferences and market perceptions across different regions would support its wider adoption. Addressing these areas through interdisciplinary research will be crucial for realizing Freekeh's potential in sustainable and health-oriented food systems.

Disclosure statement

No potential conflict of interest was reported by the authors.

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