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## A comprehensive review on the phytochemical composition and nutritional physiology of Pseudocereals

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### Abstract

Global food and nutritional security are increasingly threatened by climate change, rapid population growth, and ongoing environmental degradation. In alignment with the sustainable development goals, the elimination of hunger by 2030 requires sustainable, resource-efficient agricultural practices capable of enhancing productivity without compromising ecological integrity. In the view of increasing world population to around 10.3 billion, expanding and diversifying cropping systems through the inclusion of alternative and underutilized species has become essential for improving resilience, strengthening nutrition, and ensuring long-term food availability. Pseudocereals have gained prominence as valuable underexploited crops, representing a distinct group of non-grass species that closely mimic true cereals in grain characteristics and culinary applications despite their different botanical origins. Although, dicotyledonous, they are classified as Pseudocereals because their seeds resemble cereal grains in starch composition, texture, and cooking behaviour. Nutritionally, they provide high-quality carbohydrates, dietary fiber, and proteins with well-balanced essential amino acid profiles particularly tryptophan, lysine, arginine, histidine, as well as sulfur-rich amino acids frequently surpassing traditional cereals under favourable growing and processing conditions. They are also rich in vitamins, essential minerals such as calcium, iron, and zinc, and a diverse array of biologically active molecules including polyphenols, phytosteroids, phytosterols, betalains and saponins collectively known for their beneficial impacts on human health. Beyond their nutritional value, Pseudocereals contribute significantly to ecological sustainability and rural livelihoods due to their strong adaptability to abiotic stresses, tolerance to marginal soils, and ability to enhance agrobiodiversity. Among the various species, quinoa (*Chenopodium quinoa* Willd.), amaranth (*Amaranthus* spp.), and buckwheat (*Fagopyrum* spp.) are the most widely cultivated and extensively studied for their agronomic, nutritional, and functional potential.

### 1. Introduction

In alignment with the United Nations Sustainable Development Agenda, food insecurity and nutritional deficiencies must be eliminated through developmental processes that enhance crop yields without compromising environmental integrity or the well-being of future generations (Ain *et al.*, 2025). Increasing worldwide dietary and nutritional demand is estimated to escalate significantly, signaling an urgent need for transformative changes across food production and consumption systems (Falcon *et al.*, 2022). Despite progress in science and technology, global undernourishment still affects over 800 million individuals, while a substantial portion of the population continues to face inadequate intake of essential vitamins and minerals. The problem is intensified by the rise in severe and recurrent climate-

related events, placing a heavier burden on already vulnerable rural communities (Rukhsana and Alam, 2021). Climate change is increasingly disrupting crop production worldwide, with the vast majority of farmland now exposed to multiple environmental stresses such as high temperatures, water scarcity, soil salinity, limited nutrients, contamination, and physical strain. These combined pressures can severely diminish overall agricultural output (Kumar, 2020). The growing impacts of a changing climate worsen social and economic instability and reduce the ability of farming systems to withstand disruptions, creating a serious risk to both food availability and nutrition worldwide. Even though, hundreds of thousands of plant species have been documented globally and a considerable number are suitable for consumption, only a small fraction roughly a few hundred are grown on a large scale. Alarmingly, three major staple crops rice, wheat, and maize provide almost 60% of the world's daily carbohydrate and protein intake (Kiran *et al.*, 2022). With the global population projected to reach approximately 10.3 billion within the next few decades, ensuring an adequate food supply will require both higher yields and improved nutritional quality (UN, REPORT, 2024). Continued reliance solely on traditional staple crops will be insufficient to overcome the impending food crisis. These interlinked

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challenges highlight the urgent need to integrate alternative and underutilized crops into agricultural systems to enhance food production and build climate-resilient nutrition security.

Pseudocereals are increasingly recognized as “underexploited foods,” constituting a distinct group of non-grass plant species that, although taxonomically unrelated to true cereals, possess similar grain properties and culinary applications (Pirzadah and Malik, 2020). Botanically, Pseudocereals are dicotyledonous, unlike cereals which are monocotyledonous; however, they are classified under the term “Pseudocereals” due to the close resemblance of their seeds to cereal grains in terms of starch concentration, texture, palatability, and cooking behaviour (Poshadri *et al.*, 2024). Pseudocereals provide substantial amounts of carbohydrates, dietary fibre, and high-quality proteins, featuring a well-balanced spectrum of essential amino acids and notably higher levels of sulfur-based amino acids (Martínez-Villaluenga *et al.*, 2020). Under suitable growing and processing conditions, the protein content and nutritional quality of Pseudocereals can surpass those of traditional cereals, positioning them as promising candidates for the functional food industry (Constantino and Garcia Rojas, 2022). Their protein fractions are particularly notable for high levels of lysine, arginine, tryptophan, and histidine amino acids often limited in cereal grains. Along with their favourable protein profile, Pseudocereals also supply considerable amounts of vitamins and key minerals, including important micronutrients like calcium, iron, and zinc (Henrion *et al.*, 2020). They additionally contain a diverse range of bioactive compounds such as polyphenols, phytosteroids, phytosterols, betalains and saponins that contribute to various beneficial physiological effects (Morales *et al.*, 2021). Their importance extends beyond nutritional enrichment in regions lacking high-quality protein sources, offering socioeconomic advantages in areas where food production capacity is constrained. From an environmental standpoint, Pseudocereals contribute to enhancing natural resource diversity and strengthening agricultural sustainability (Manoharan *et al.*, 2025). Their agronomic traits including resilience to abiotic stresses, ecological adaptability, and tolerance to marginal soils combined with their high nutritional value underscore their economic, social, ecological, functional, and nutritional relevance (Rodríguez *et al.*, 2020). Among the Pseudocereals, quinoa (*Chenopodium quinoa* Willd.), amaranth (*Amaranthus* spp.), and buckwheat (*Fagopyrum* spp.) are the most widely cultivated and extensively studied (Nagaraja *et al.*, 2024).

In India, the cultivation of Pseudocereals including grain amaranth, quinoa, and buckwheat has been practiced for many years, forming part of the country’s traditional agricultural landscape. Within the country, the Northeastern hill region is particularly notable for the extensive cultivation of grain amaranth and buckwheat, largely due to its favorable agro-climatic conditions that support the successful growth of these crops (Patil and Jena, 2020). The ongoing cultivation of Pseudocereals in this region underscores India’s rich agricultural biodiversity and illustrates the country’s increasing focus on leveraging these lesser-used crops for their dietary value and economic benefits. In this review paper, a comprehensive overview of the phytochemical composition and nutritional attributes of these major Pseudocereals has been presented. Despite the increasing number of reviews on Pseudocereals, most articles focus either on a single crop, highlighting specific biochemical aspects, or offers general overviews without including recent developments. There is still a lack of thorough synthesis that compares amaranth, quinoa, and buckwheat in areas

like agronomy, nutritional quality, bioactive composition, therapeutic value, and antinutritional factors. This review addresses these gaps by synthesizing updated multidisciplinary evidence on the nutritional composition, antinutritional factors and therapeutic potential of major Pseudocereals, while also integrating cross-crop comparisons and outlining the key production and utilization challenges that must be overcome to enhance their contribution to sustainable food and nutrition systems.

## 2. Methodology

A comprehensive literature search was carried out to compile current evidence on the nutritional composition, bioactive constituents, and functional attributes of quinoa, amaranth, and buckwheat. The search was conducted across Scopus, Web of Science, PubMed, and Google Scholar using combinations of controlled vocabulary and free-text terms, including “Pseudocereals”, “quinoa”, “amaranth”, “buck wheat”, “nutritional value”, “phytochemicals”, “phenolic compounds”, “bioactive compounds”, “anti-nutritional factors”, and “proximate composition”. The search covered publications from 2020 to 2025 and was limited to peer-reviewed articles published in English. Studies were included if they provided quantitative data relevant to nutrient composition, secondary metabolites, functional properties, or processing effects. Publications were excluded if they lacked extractable data, were review articles without primary data, were non-scientific sources, or presented duplicated information. Reference lists of key articles were screened to capture additional relevant studies not identified in the initial search.

## 3. Pseudocereals

Pseudocereals are fruits or seeds of non-grass plant species that are consumed in a manner similar to true cereals and are often nutritionally comparable or even superior to conventional cereal crops (Nagaraja *et al.*, 2024). They are dicotyledonous grains regarded as viable alternatives to cereals found in the monocotyledonous Poaceae family (Poshadri *et al.*, 2024). The major Pseudocereals namely Amaranth, Quinoa and Buckwheat are discussed below. Figure 1 shows the field images of major Pseudocereals discussed.

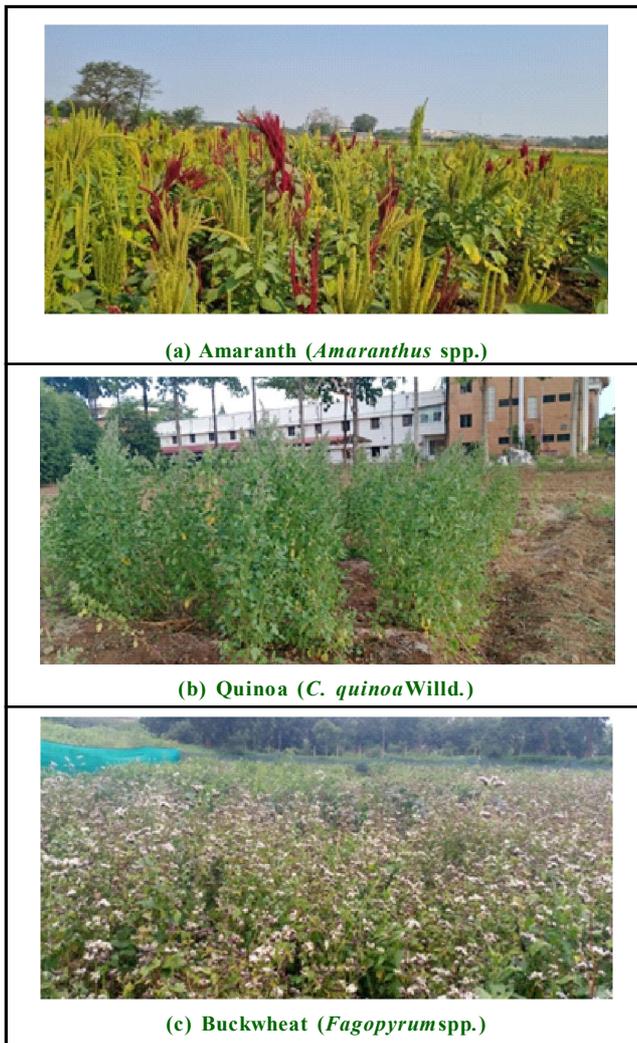
### 3.1 Amaranth (*Amaranthus* spp.)

#### 3.1.1 Origin and distribution

Amaranth, classified under the genus *Amaranthus*, encompasses a diverse range of species that include those grown for edible seeds, leafy vegetables, decorative purposes, and those occurring as natural weeds. Historically, its seed forms were a key component of the diet of ancient Mesoamerican civilizations, particularly the Aztecs, who cultivated it extensively across regions that today correspond to Mexico and Central America (Malik *et al.*, 2023). In modern agriculture, this crop has attracted renewed interest due to its remarkable capacity to tolerate adverse environmental conditions and its capacity to produce substantial vegetative matter and seed yield. Presently, grain amaranth is cultivated across Central and South America, as well as in parts of Asia and Africa (Baraniak and Kania-Dobrowolska, 2022).

#### 3.1.2 Economic parts

Amaranth leaves are consumed as vegetables, while its grains are used similarly to cereals. The seed heads, which may reach up to 50 cm in length, similar to sorghum, while the seeds themselves are minute, measuring approximately 0.9-1.7 mm in diameter (Baraniak and Kania-Dobrowolska, 2022).



**Figure 1:** (a) (b) (c) - Major Pseudocereals.

### 3.1.3 Nutritional and health benefits

As a highly nutritious pseudocereal, amaranth is characterized by its elevated protein content, contributing to its value in human diets. Including it in the diet can help maintain balanced cholesterol, and its inherently low salt and fat levels make it a good choice for managing body weight (Rivero Meza *et al.*, 2023). Furthermore, amaranth exhibits anticancer potential and is naturally gluten-free, making it suitable for individuals with specific dietary restrictions (Sattar *et al.*, 2024). Amaranth grains contain high-quality proteins such as albumin, globulin, glutelin, and prolamins and also a significant contributor of folate in the diet, often exceeding quantities than reported in conventional cereals (Zhang *et al.*, 2023). Around the world, it is consumed in various forms, and its flour is incorporated into diverse edible products such as baked goods and noodles - pasta based products (Sattar *et al.*, 2024). Owing to its naturally high levels of calcium and iron, amaranth contributes meaningfully to dietary nutrition and is particularly advantageous for sportspeople, individuals managing type 2 diabetes, those with gluten intolerance or coeliac disease, and populations facing nutritional deficiencies (Nyonje *et al.*, 2021).

## 3.2 Quinoa (*C. quinoa*)

### 3.2.1 Origin and distribution

Quinoa (*C. quinoa*) is a member of the Chenopodiaceae family, which also comprises species such as beetroot and spinach. This crop is native to South America and was domesticated thousands of years ago in the Andean region, particularly in present-day Peru and Bolivia, where it held great cultural and spiritual significance (Pathan and Siddiqui, 2022).

### 3.2.2 Nutritional and health benefits

Although, both the seeds and leaves are edible, the seeds have received the most attention in economic and scientific investigations. This crop is notable for its comparatively elevated protein content - typically between 12% and 23%, varying across genotypes placing it above many conventional cereal grains (Gómez *et al.*, 2021). Its protein quality is also exceptional, offering a balanced spectrum of essential amino acids, including notably higher proportions of lysine, histidine, and methionine, which are usually present in limited amounts in most staple cereals (Ranjan *et al.*, 2023). The crop is also highly tolerant to diverse climatic, environmental, and soil conditions. In addition to its superior protein quality, quinoa contains sugars such as ribose, galactose, and maltose, and provides an exceptional amino acid composition essential for human nutrition (Pathan and Siddiqui, 2022). The crop is particularly rich in biologically active constituents, including phytosterols, saponins, and phytoecdysteroids that contribute to various beneficial effects to human body (Pathan and Siddiqui, 2022). Its protein fraction is dominated by albumin and globulin. The crop is also noted for its high levels of non-protein tryptophan, which is rapidly absorbed and supports neurotransmitter synthesis (especially serotonin) in the brain (Chaudhary *et al.*, 2023). Moreover, quinoa is naturally low in saturated fat, free of cholesterol, high in dietary fiber, and low in sodium, all of which support healthy digestion and may reduce the risk of kidney and gallbladder stone formation (Ren *et al.*, 2023). In addition to these attributes, quinoa is abundant in antioxidants and provides significant amounts of key vitamins, including vitamins E, C, and B, further contributing as a nutritious and functional pseudocereal (Pedrali *et al.*, 2023).

## 3.3 Buckwheat (*Fagopyrum* spp.)

### 3.3.1 Origin and distribution

Buckwheat traces its origin to Asia and has been cultivated for more than 3,000 years. It is known for its strong adaptability to harsh environmental conditions and its short growth duration. Buckwheat has been cultivated for centuries for both its grains and greens, serving as a source of food, feed, vegetables, and fodder (Koval *et al.*, 2020). However, its cultivation declined in Western countries during the 20<sup>th</sup> century due to the increased productivity of wheat following the Green Revolution. At present, buckwheat cultivation is concentrated mainly in countries such as Russia, Ukraine, and China, though it is also grown to a lesser extent across various other regions (Huda *et al.*, 2021). In recent decades, the crop has attracted renewed interest due to its suitability for organic farming systems and its growing use in nutrition-focused food products.

### 3.3.2 Cultivated species

Among the cultivated species, common buckwheat (*F. esculentum*), dominates global production, contributing nearly 90% of the total

yield worldwide (Bani *et al.*, 2025). Tartary buckwheat (*F. tataricum*) is another important species, mostly grown in mountainous regions at higher altitudes due to its greater tolerance to frost (Zamaratskaia *et al.*, 2024).

### 3.3.3 Economic parts

Buckwheat is a broadleaf crop within the order Caryophyllales, sharing taxonomic placement with amaranth and quinoa, and is not botanically connected to wheat (Mukhtar *et al.*, 2021). Globally, buckwheat is widely used in noodle and pasta preparations, with its seeds constituting the main edible part, while the leaves are also valued for their beneficial health attributes (Kreft *et al.*, 2023).

### 3.3.4 Nutritional and health benefits

Buckwheat contains substantial amounts of resistant starch; a component known to support intestinal health and potentially lower the likelihood of developing colorectal disorders. It also provides a valuable supply of proteins, unsaturated lipids, and essential vitamins, with albumin and globulin representing its major protein groups (Jin *et al.*, 2022). The high fiber content plays an important role in maintaining healthy lipid levels in the blood and reduces the risk of various chronic health conditions. Additionally, buckwheat contains a wide range of bioactive flavonoids, including procyanidin B-2, orientin, vitexin, quercetin, isovitexin, rutin, kaempferol-rutinoside, and hyperin (Jin *et al.*, 2022).

## 4. Nutritional composition of Pseudocereals

Pseudocereals have recently become popular as highly nutritious ingredients in gluten-free diets, serving as healthy substitutes for traditional gluten-containing grains. In addition to their dietary value, they are recognized for offering several health-promoting benefits, including anti-inflammatory, anticancer and immune-enhancing properties (Morales *et al.*, 2021). The nutritional profile of major Pseudocereals including amaranth, quinoa and buckwheat is summarized in Table 1. Per 100 g, amaranth provides 13500-13800 mg of protein, 6900-7200 mg of fat, 66500-67000 mg of carbohydrates, 160-165 mg of calcium and 4.4-4.8 mg of iron,

contributing to roughly 320 kcal of energy. Likewise, a 100 g portion of quinoa contains about 14000-14300 mg of protein, 6000-6200 mg of fat, 63800-64500 mg of carbohydrates, 145-152 mg of calcium and 13.0-13.4 mg of iron, yielding around 368 kcal of energy. Similarly, 100 g of buckwheat offers approximately 13200-13400 mg of protein, 3350-3450 mg of fat, 71300-71700 mg of carbohydrates, 17-19 mg of calcium and 2.1-2.3 mg of iron, providing an energy value of about 368 kcal.

Unlike the most traditional cereals, the proteins in amaranth, quinoa, and buckwheat are mainly composed of globulins and albumins, while prolamins represent only a minor fraction. These Pseudocereals exhibit an excellent amino acid profile, containing higher levels of methionine, cysteine, and lysine. Importantly, quinoa and amaranth provide substantial amounts of lysine, an essential amino acid that is usually present at low concentrations in conventional cereals (Martínez-Villaluenga *et al.*, 2020). Pseudocereals are characterised by a favourable amino acid composition, particularly their elevated levels of arginine and histidine, which support the nutritional demands of infants, toddlers, and growing children (Vajdovich *et al.*, 2025). In contrast, most cereal grains store their proteins predominantly as prolamins compounds that are strongly implicated in triggering celiac disease. Another distinguishing feature of Pseudocereals is their lipid profile. Quinoa (4.0-7.6%), buckwheat (0.7-7.4%), and amaranth (3.24-10.9%) contain substantially increased fat levels than conventional cereals (Raungrusmee, 2023). These lipids are largely composed of unsaturated fatty acids, including notable proportions of  $\omega$ -3 and  $\omega$ -6 fatty acids. The regular intake of  $\omega$ -3 and  $\omega$ -6 fatty acids has been widely associated with reduced biomarkers and risk factors for several chronic conditions, such as cardiovascular diseases, cancer, osteoporosis, inflammatory disorders, and autoimmune diseases. Consequently, the predominance of unsaturated fatty acids in Pseudocereals enhances their value as functional foods with significant therapeutic potential (Pirzadah and Malik, 2020). Buckwheat contains a greater proportion of carbohydrate compared with quinoa and amaranth. Due to its high calcium content, amaranth is often recommended for individuals with celiac disease who are affected by osteopenia or osteoporosis (Nagar *et al.*, 2022).

**Table 1: Nutritional composition of Pseudocereals**

Crop	Value per 100 g						Sources
	Energy (kcal/100 g)	Protein (mg/100 g)	Fat (mg/100 g)	Carbohydrate (mg/100 g)	Ca (mg/100 g)	Fe (mg/100 g)	
Amaranth	318-322	13,500-13,800	6,900-7,200	66,500-67,000	160-165	4.4-4.8	G20 AWG, 2023; Millets report, 2024; Nandan <i>et al.</i> , 2024
Quinoa	365-370	14,000-14,300	6,000-6,200	63,800-64,500	145-152	13.0-13.4	G20 AWG, 2023; Millets report, 2024; Raj and Paliwal, 2024; Nandan <i>et al.</i> , 2024
Buckwheat	340-345	13,200-13,400	3,350-3,450	71,300-71,700	17-19	2.1-2.3	G20 AWG, 2023; Millets report, 2024; Nandan <i>et al.</i> , 2024

**Legend:** Energy, protein, fat, carbohydrate, calcium and iron values are standardized to per 100 g on a dry weight basis. Fat and carbohydrate values were converted from grams to milligrams. Ranges represent minimum and maximum values reported across the referenced studies.

## 5. Phytochemical composition of Pseudocereals

### 5.1 Bioactive compounds of Amaranth

#### 5.1.1 Phenolic compounds

Bioactive phytochemicals in amaranth are primarily concentrated in the outer seed layers, where they function as natural chemical defenses against insects and microorganisms. These compounds may be hydrophilic or lipophilic in nature (Manyelo *et al.*, 2020). Among them, phenolic acids (largely hydrophilic) are located predominantly in the seed coat and constitute the major secondary metabolites responsible for various physiological effects (Bang *et al.*, 2024). Characterization of phenolics in *Amaranthus* species has revealed the presence of common plant-derived hydroxybenzoic acids such as salicylic acid, vanillic acid, gallic acid, ellagic acid, and p-hydroxybenzoic acid. In addition, several hydroxycinnamic acids have been identified in *A. hypochondriacus* leaves, including caffeic acid, p-coumaric acid, chlorogenic acid, m-coumaric acid, sinapic acid, ferulic acid, and trans-cinnamic acid, with sinapic acid being the most abundant (Singhania *et al.*, 2023). Analysis of amaranth seed and leaf extracts by Jeong *et al.* (2020) revealed that the seeds contain substantial levels of 2,4-dihydroxybenzoic acid and kaempferol, while the leaves possess a wider variety of phenolic compounds. The study also identified six previously unreported phenolic compounds, and the seeds were found to potentially contain 2,3-dihydroxy benzaldehyde, a bioactive compound with notable health benefits.

#### 5.1.2 Flavonoids

The predominant flavonoids in amaranth are quercetin and isorhamnetin, accompanied by smaller amounts of myricetin, rhamnetin, and kaempferol across different cultivars (Bang *et al.*, 2024). Isoquercetin (quercetin-3-glucoside) and rutin (quercetin-3-rutinoside) are the most common flavonoid derivatives consistently detected in all amaranth varieties (Bang *et al.*, 2021). The biological constituents of amaranth namely rutin and other phenolic amide compounds, contributes to protection against free radicals that causes oxidation of compounds and help mitigate memory impairment. Araujo-León *et al.* (2024) demonstrated through HPLC profiling that the major flavonoids present were quercetin, kaempferol, catechin, and hesperetin. Among these, quercetin - detected predominantly in its aglycone form - was the most abundant, with concentrations reaching 1361 µg/g in the leaves and 77.28 µg/g in the inflorescences.

#### 5.1.3 Betalains

Betalains are nitrogen-rich indole-derived pigments produced through the tyrosine biosynthetic pathway and are uniquely found in plant species belonging to the order Caryophyllales, including those in the Amaranthaceae family (Kumari and Khan, 2025). In amaranth, compounds such as amaranthine function as biologically derived coloring agents widely accepted to be used in food and pharmaceutical formulations (Carreón-Hidalgo *et al.*, 2022). Studies examining betalain levels in different amaranth cultivars have shown notable variations in pigment composition and antioxidant capacity. However, findings indicate that the antioxidant activity of these cultivars is influenced more by phenolic compounds than by betalains (Carreón-Hidalgo *et al.*, 2022; Howard *et al.*, 2022).

### 5.2 Bioactive compounds of Quinoa

#### 5.2.1 Phenolic compounds

In quinoa seeds, a broad spectrum of phenolic acids has been reported, including vanillic, protocatechuic, ferulic, caffeic, p-coumaric, 4-hydroxybenzoic, and 8,52 -diferulic acids, along with various related derivatives (Pandya *et al.*, 2023). It contains free phenolic compounds ranging from approximately 167.2 to 308.3 mg gallic acid equivalents per 100 g of dry weight (Ocampo *et al.*, 2023). In seven quinoa varieties, the free phenolic fraction accounted for about 53.5% to 78.0% of the total phenolic content, with ferulic acid and gallic acid being the dominant constituents (Hussain *et al.*, 2021). Quinoa also possesses a range of bound phenolic compounds that are linked to the structural matrix of the seed. These phenolics are typically attached to cell wall constituents, including lignin, pectin, hemicelluloses such as arabinoxylans, cellulose, and various structural proteins (Ranjan *et al.*, 2023). However, the amount of bound phenolics in quinoa seeds is lower than that of free phenolics, and these bound forms are more commonly found in quinoa leaves than in the grains. The liquid chromatography method developed by Qian *et al.* (2023) facilitated the simultaneous detection of phenolic compounds and saponins in quinoa using a fused-core C18 column with a total run time of less than 27 minutes. The analysis tentatively identified 25 free and 5 bound phenolic compounds, including several not previously reported in quinoa. Free phenolic contents ranged from 2.746 to 3.803 g/kg, while bound phenolics ranged from 0.139 to 0.164 g/kg. Dietary phenolic compounds play an important role in maintaining gastrointestinal health by influencing the composition and activity of the gut microbiota (Sageena *et al.*, 2025).

#### 5.2.2 Saponins

Saponins are bitter-tasting secondary metabolites concentrated primarily in the pericarp of quinoa seeds. Chemically, they are glycosidic compounds composed of one or more sugar residues attached to a triterpenoid or steroidal aglycone (El Hazzam *et al.*, 2020). In quinoa, the predominant saponins belong to the triterpene glycoside group and are largely derived from aglycones such as hederagenin, phytolaccagenic acid, oleanolic acid, serjanic acid, and several related hydroxy-oleanane structures (Lim *et al.*, 2020). The saponin content in quinoa varies by cultivar, allowing it to be classified as either “sweet” (containing less than 0.11% saponins) or “bitter” (containing more than 0.11%) (Otterbach *et al.*, 2021). Bitter varieties generally contain higher concentrations than sweet types. These compounds play an important role in natural crop protection by deterring insects, birds, and microbial pathogens, thereby supporting organic cultivation practices (El Hazzam *et al.*, 2020). Their inclusion in the diet has been associated with reduced blood cholesterol levels due to their interaction with blood cells. Although, they are not harmful to human health when consumed, excessive saponin levels can reduce protein digestibility and nutrient bioavailability (Prajapati and Singh, 2024). The functional attributes of quinoa saponins contribute to a range of health-promoting effects, including antiviral, antifungal, anticancer, antithrombotic, hypocholesterolemic, diuretic, hypoglycemic, and anti-inflammatory activities.

#### 5.2.3 Phytoecsteroids

Among plant secondary metabolites, phytoecdysteroids play an important defensive role by protecting plants against insect pests and nematodes. These compounds are polyhydroxylated molecules

characterized by a cyclopentanoperhydrophenanthrene ring structure, although their exact structural configurations vary widely among plant species (Lafont *et al.*, 2021). Quinoa is the only major pseudocereal known to contain substantial quantities of phytoecdysteroids, typically ranging from 138 to 570  $\mu\text{g/g}$  (Poonia *et al.*, 2024). The plant produces around 36 different phytoecdysteroid types, with C-27 phytoecdysteroids occurring in the highest concentrations and offering notable health benefits (Arif *et al.*, 2022). Phytoecdysteroids are recognized for their antiageing properties, largely due to their strong antioxidant capacity, which includes metal ion chelation and free radical scavenging activities. They have also been explored as a safe and natural alternative to anabolic steroids (Adetunji *et al.*, 2022). Furthermore, these bioactive compounds support the development of skeletal muscle, contributing to improved physical performance and overall muscular strength.

#### 5.2.4 Betalains

Betalains are water-soluble phytochemicals found in quinoa that act as natural antioxidants and contribute to cancer-preventive properties. These pigments contribute to the distinctive red, black, and yellow hues observed in quinoa seeds and various plant tissues (Liu *et al.*, 2020). Betalains consist of red-violet and orange-red betaxanthins, which are nitrogen-containing indole derivatives formed from tyrosine (Causin *et al.*, 2025). The presence and concentration of betalains vary widely among quinoa varieties; some seeds contain measurable amounts ranging from approximately 0.15 to 6.10 mg per 100 g, while others contain only trace levels (Yang *et al.*, 2024). Quinoa seeds typically contain high proportions of betanin and isobetanin, both of which possess strong antioxidant, antibacterial, and anti-inflammatory activities (Olivera *et al.*, 2022). Betalains are known to exhibit even greater antioxidant potential than polyphenols, making them valuable bioactive molecules with anticancer, antimicrobial, antilipidemic, and overall health-promoting effects (Liu *et al.*, 2020). Recent studies have explored microencapsulation techniques to enhance the stability of these pigments. Notably, maltodextrin-based microencapsulation systems enriched with betacyanins and reduced saponin content have shown promising functional and therapeutic properties (Guía-García *et al.*, 2022).

#### 5.2.5 Flavonoids

Quinoa seeds contain several important flavonoids, primarily rutin, quercetin, and kaempferol derivatives. The plant also contains a broad array of associated phenolic molecules, including syringic acid, ferulic acid, benzoic acid, p-coumaric acid, and vanillic acid. Flavonoids represent the major abundant group of bioactive compounds in quinoa, with flavonol glycosides being the dominant class present in both the leaves as well as seeds (Lafont *et al.*, 2021). Quinoa is known to contain at least twelve types of flavonol glycosides, mainly derived from kaempferol and quercetin (Li *et al.*, 2021). These plant-based flavonoids, including isoflavones, are recognized for their significant health benefits, contributing to antioxidant, anti-inflammatory, and protective physiological effects in humans.

### 5.3 Bioactive compounds of Buckwheat

#### 5.3.1 Flavonoids

Buckwheat is particularly valued for its rich content of bioactive flavonoids with diverse therapeutic applications. Several flavonoids have been identified in Buckwheat, including quercetin, isoquercetin,

rutin, procyanidin B2, catechin, epicatechin, luteolin, and kaempferol (Kreft *et al.*, 2023). Notably, rutin is a key flavonoid found exclusively in buckwheat among Pseudocereals. Tartary Buckwheat contains significantly higher flavonoid levels approximately 40 mg/g in major parts such as seeds, flowers and leaves compared to common buckwheat, which contains around 10 mg/g (Shen *et al.*, 2024). Flavonoids comprise several subgroups, including isoflavones, flavanones, flavones, flavanols, proanthocyanins, anthocyanins, flavonolignans, and species-specific *Fagopyrum* compounds (Bani *et al.*, 2025). Flavones are an important subgroup, with variable concentrations found in the leaves, seeds, stems, flowers, cereals, and husks of different *Fagopyrum* varieties. Four major flavones orientin, vitexin, isovitexin, and isoorientin were recorded in common buckwheat sprouts (Zou *et al.*, 2023). Analyses of Buckwheat hulls have shown clear differences between the two major cultivated species. Extracts from common buckwheat are typically rich in several C-glycosyl flavones namely orientin, isoorientin, vitexin, and isovitexin (Sofi *et al.*, 2023). In contrast, hull extracts from Tartary buckwheat contain a more limited flavonoid profile, with isoorientin being the predominant compound reported.

Flavonols are the predominant bioactive compounds in Buckwheat, with rutin constituting about 90% of all phenolic compounds. Rutin, a quercetin glycoside (quercetin-3- $\beta$ -D-rutinoside), exhibits numerous therapeutic effects, including improved vascular elasticity, protection against circulatory disorders and atherosclerosis, antioxidant and anti-inflammatory activity, antihypertensive effects, UV protection, cholesterol reduction, and mitigation of oxidative stress and gastric lesions (Li *et al.*, 2025). Flavonoids have been detected across Buckwheat plant parts, including hull, roots, flowers, berries, grains, germinating seeds, and various processed products. Studies have reported 24 different flavanones from common and Tartary Buckwheat, including phloretin, eriodictyol derivatives, homoeriodictyol, hesperetin derivatives, naringenin and its derivatives, isoliquiritigenin, pinocembrin, xantho-humol, afzelechin, isosakuranetin, and naringenin-chalcone (Sonawane *et al.*, 2024; Zhao *et al.*, 2024).

Anthocyanins pigments responsible for coloration in plants are also present in Buckwheat. A total of 18 anthocyanin types have been identified in common Buckwheat, including peonidin derivatives, delphinidin derivatives, cyanidin derivatives, malvidin 3,5-diglucoside, petunidin 3-O-glucoside, pelargonidin 3-O- $\beta$ -D-glucoside, and rosinidin derivatives (Deng *et al.*, 2023). Tartary Buckwheat sprouts contain higher anthocyanin levels than common Buckwheat sprouts, contributing to reduced cardiovascular risk (Zargar *et al.*, 2024). Isoflavones such as glycitin, 6-hydroxydaidzein, sissotrin, 2-hydroxydaidzein, formononetin, genistein-7-O-glucoside, and related compounds have been extracted from common and Tartary Buckwheat species (Ke *et al.*, 2023). Another flavonoid-type compound, fagopyrin, occurs mainly in low-density tissues. Common Buckwheat flowers and leaves contain 4.83 mg/g and 0.322 mg/g of fagopyrin, respectively (Lei *et al.*, 2024). Fagopyrin levels peak during seed germination, and sunlight is required to convert protofagopyrins into active fagopyrins, increasing their concentration (Ke *et al.*, 2023).

#### 5.3.2 Phenolic acids

Buckwheat is recognized as one of the richest sources of phenolic acids, which occur in both free and bound forms. Here, the predominant phenolic acids arise mainly from cinnamic and benzoic

acid pathways. A diverse set of these compounds has been reported, including chlorogenic, salicylic, caffeic, gallic, ferulic, syringic, vanillic, protocatechuic, *p*-coumaric, and *p*-hydroxybenzoic acids (Chen *et al.*, 2021). These compounds contribute significantly to the crop's antioxidant capacity and play an essential role in protecting seeds from chemical deterioration during long-term storage. As natural antioxidants, phenolic acids help neutralize reactive oxygen species and are associated with reducing the risk of cardiovascular diseases, cancer, and various age-related disorders.

### 5.3.3 Triterpenoids

Across different *Fagopyrum* species, a total of seven triterpenoids have been identified. In Tartary Buckwheat,  $\alpha$ -thujene and  $\alpha$ -terpineol are the major compounds, while ursolic acid has been reported in multiple Buckwheat species, including both the tartary type and the cymosum group, demonstrating its wider distribution within the genus (Zhong *et al.*, 2021). In common Buckwheat, the seed oil contains triterpenoids such as urs-12-an-3-ol and as olean-12-en-3-ol.

The rhizomes of *F. cymosum* also yield glutinol and glutinone. These triterpenoids exhibit strong anti-inflammatory properties and contribute to reducing the risk of cardiovascular diseases (Kreft *et al.*, 2023).

### 5.3.4 Phenylpropanoid glycosides

Thirteen phenylpropanoid glycosides have been reported across various *Fagopyrum* species. In Tartary Buckwheat roots, compounds such as tatariside A and diboside A have been isolated, with diboside A also present in *F. cymosum* (Choi *et al.*, 2021). Additionally, several complex phenylpropanoid sucrose esters have been identified in Tartary Buckwheat seeds, including 3,6-di-*p*-coumaroyl-1,6-di-feruloyl sucrose, 1,3,6-tri-feruloyl-6-*p*-coumaroyl sucrose, and 1,3,6,6-tetra-feruloyl sucrose (Yang *et al.*, 2022). The phenylpropanoid glycosides demonstrate notable anti-inflammatory activity and play a protective role in reducing heart related ailments. Figure 2 summarizes all the major bioactive compounds in Pseudocereals and their health benefits.

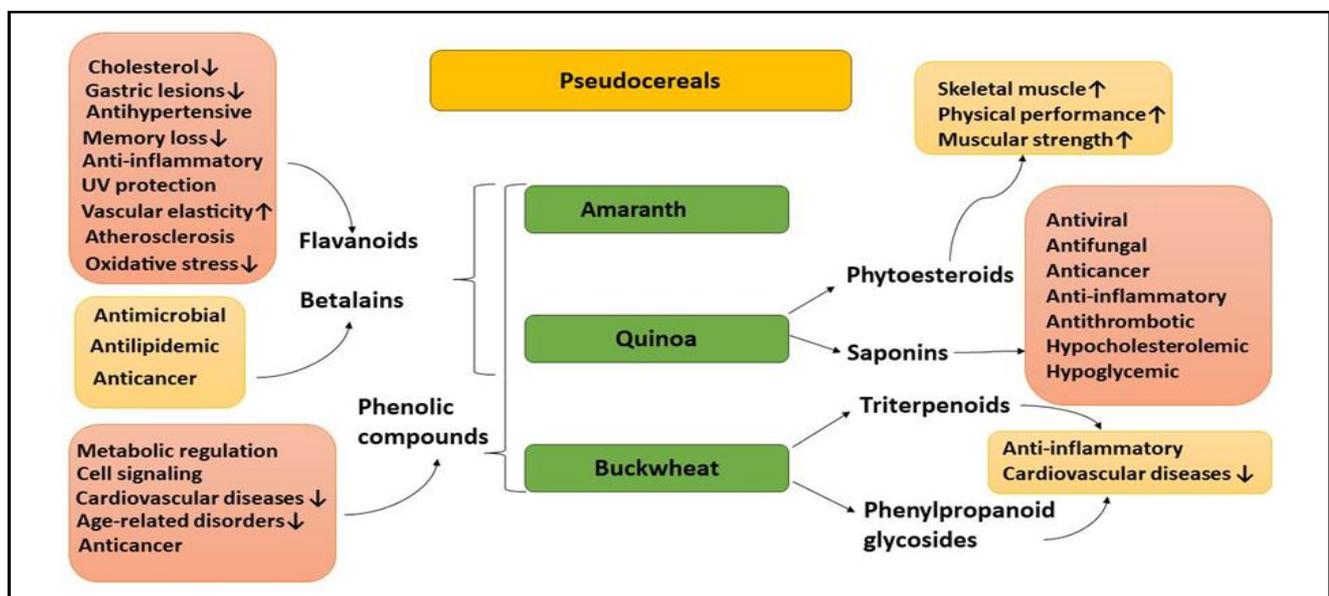


Figure 2: Overall biological activity and health benefits of Pseudocereals.

## 6. Nutritional and therapeutic value of Pseudocereals

Numerous research analyses have explored the potential of amaranth,

quinoa, and buckwheat in the management of various ailments. Table 2 elaborately explains the health benefits of the major Pseudocereals.

Table 2: Key health benefits of major Pseudocereals

Amaranth				
Bioactive compound	Key features	Range (mg g <sup>-1</sup> FW or IC <sub>50</sub> half maximal inhibitory concentration)	Health benefits	References
Total phenolic content (TPC)	Phenolic acids	6.35-19.69 mg GAE g <sup>-1</sup> FW	Exhibits antioxidant and anti-inflammatory activity; <i>in vitro</i> studies suggest potential protection of lipids and DNA	De Souza <i>et al.</i> , 2022
Total flavonoid content (TFC)	Quercetin, rutin, apigenin	3.99-20.37 mg QE g <sup>-1</sup> FW	Associated with antidiabetic, anti-obesity, hepatoprotective and cardioprotective effects in experimental models; contributes to antioxidant defence	De Souza <i>et al.</i> , 2022

Dihydroflavonoids	Hydroflavonoids	1.06-4.05 mg EN g <sup>-1</sup> FW	Demonstrates antioxidant and anti-inflammatory activity in <i>in vitro</i> assays; may support vascular protection	Thakur <i>et al.</i> , 2021
Vitamin C (ascorbic acid)	Water soluble antioxidant vitamin	109.20-174.18 mg 100 g <sup>-1</sup>	Contributes to antioxidant capacity, immune support, and iron absorption based on known physiological roles	De Souza <i>et al.</i> , 2022
Antioxidant capacity (DPPH IC <sub>50</sub> )	Free radical scavenging ability	0.67-12.45 mg ml <sup>-1</sup> (IC7EE); lower IC7EE = better activity	Indicates strong <i>in vitro</i> radical scavenging potential; suggests possible relevance in reducing oxidative stress	Al-Tamimi <i>et al.</i> , 2021
ABTS radical scavenging (IC <sub>50</sub> )	ABTS radical	1.06-4.00 mg m <sup>-1</sup> (IC7EE)	Shows antioxidant and anti-inflammatory activity in <i>in vitro</i> systems; potential anti-aging relevance requires further validation	De Souza <i>et al.</i> , 2022
Total antioxidant capacity (CAT)	Measures total reducing power	0.19-2.73 mg EAA g <sup>-1</sup>	Reflects reducing capacity in chemical assays; may help protect biomolecules from oxidative damage	De Souza <i>et al.</i> , 2022
Chelating power (IC <sub>50</sub> )	Ability to bind prooxidant metal ions	0.00-36.72 mg ml <sup>-1</sup> (IC <sub>50</sub> )	Demonstrates metal chelating activity in <i>in vitro</i> assays, suggesting potential to reduce prooxidant metal effects	De Souza <i>et al.</i> , 2022
Pigments (Chroma, Hue, Colourintensity)	Betalains and chlorophyll related pigments	Chroma: 11.90-21.14; Hue: 33.66-123.16	Exhibits antioxidant and anti-inflammatory properties; anticancer activity reported only in <i>in vitro</i> studies	Gins <i>et al.</i> , 2020
<b>Quinoa</b>				
Bioactive compound	Key features	Range	Health benefits	References
Total phenolic content (TPC)	Phenolic acids	Leaves: 131.8-544 mg GAE/100 g DW Sprouts: 49.02-417.75 mg GAE/100 g DW Grains: 39.29-198.23 mg GAE/100 g DW	Exhibits strong antioxidant and anti-inflammatory activity; <i>in vitro</i> studies indicate potential anticancer and cardioprotective effects (not clinically established)	Huang <i>et al.</i> , 2025
Total flavonoid content (TFC)	Quercetin, rutin, kaempferol	Leaves: 8.69-62.07 mg QE/100 g DW Sprouts: 10.38-304.10 mg QE/100 g DW Grains: 11.40-223.80 mg QE/100 g DW	Shows antioxidant activity and exhibits antidiabetic, antiobesity and vasoprotective effects in experimental models; evidence is largely based on <i>in vitro</i> and <i>in vivo</i> studies	Huang <i>et al.</i> , 2025
Antioxidant capacity (DPPH)	Free radical scavenging ability	Leaves: 29.90-65.30 mg TE/100 g DW Sprouts: 5.26-61.41 mg TE/100 g DW Infructescence: ~95 mg TE/100 g DW	Indicates strong <i>in vitro</i> antioxidant capacity; suggests potential to reduce oxidative stress and protect biomolecules, though clinical relevance remains unverified	Li <i>et al.</i> , 2021
Carotenoids (total and β-carotene)	Vitamin A precursors	Leaves: 8.20-90.50 mg/100 g Sprouts: 8.11-15.58 mg/100 g (6 days old) β-carotene: 12.42-32.71 mg/100 g FW (25 days old sprouts)	Contribute to antioxidant activity and support physiological functions related to vision and immunity; effects are based on nutrient properties, not quinoa-specific clinical trials	Al-Qabba <i>et al.</i> , 2020
Flavonoid types identified	Quercetin, kaempferol, rutin	Not quantified individually	Exhibits antioxidant and anti-inflammatory potential; <i>in vitro</i> studies suggest anticancer, cardioprotective and antidiabetic activity	Al-Qabba <i>et al.</i> , 2020
Other bioactive compounds	Polyphenols, carotenoids, tocopherols, phytoecdysteroids, phytosterols, peptides, saponins, tannins, phytic acid	Not quantified	Associated with cholesterol modulating, antimicrobial and metabolic regulatory effects in experimental studies; activities are indicative of potential function, not confirmed therapeutic outcomes	Pathan and Siddiqui, 2022

<b>Buckwheat</b>				
TBW = Tartary Buckwheat ( <i>F. tataricum</i> )				
CBW = Common Buckwheat ( <i>F. esculentum</i> )				
Bioactive compound	Key features	Range	Health benefits	References
Total phenolic content (TPC)	Phenolic acids	Overall variety range: TBW: 842.14-2101.42 mg GAE/100 g CBW: 704.71-1980.58 mg GAE/100 g Milling fractions: Husk (TBW): 1024.19 mg GAE/100 g Fine flour (TBW): 155.23 mg GAE/100 g Husk (CBW): 907.70 mg GAE/100 g Fine flour (CBW): 110.23 mg GAE/100 g	Exhibits strong antioxidant and anti-inflammatory activity; <i>in vitro</i> studies suggest potential anticancer and cardioprotective effects (not clinically validated)	Mazahir <i>et al.</i> , 2022
Total flavonoid content (TFC)	Rutin, quercetin, vitexin, isoorientin, isovitexin	Overall variety range: TBW: 261.28-1233.99 mg QE/100 g CBW: 214.68-1088.62 mg QE/100 g Milling fractions: Husk (TBW): 734.89 mg QE/100 g Fine flour (TBW): 122.83 mg QE/100 g Husk (CBW): 693.11 mg QE/100 g Fine flour (CBW): 103.40 mg QE/100 g	Shows antioxidant activity; experimental studies report antidiabetic, antihypertensive, and vasoprotective potential; effects largely based on <i>in vitro</i> and <i>in-vivo</i> evidence	Kreft <i>et al.</i> , 2023
DPPH radical scavenging (antioxidant activity)	Percentage of free radical scavenging	Overall variety range: TBW: 17.18-44.51% CBW: 15.02-34.47% Milling fractions: Husk (TBW): 25.93% Fine flour (TBW): 11.67% Husk (CBW): 22.59% Fine flour (CBW): 2.92%	Indicates strong <i>in vitro</i> antioxidant capacity; suggests potential protection against oxidative stress and biomolecule damage; antiageing effects are preliminary and not clinically established	Mazahir <i>et al.</i> , 2022

**Note:** The listed health effects are based primarily on biochemical composition and *invitro/invivo* evidence. These activities indicate biological potential but do not represent clinically validated therapeutic outcomes.

## 7. Antinutritional factors in Pseudocereals

In quinoa (*C. quinoa*), the dominant antinutrient saponins are primarily located in the seed coat and have been quantified at approximately 0.01-4.65/ % of seed weight, with specific studies reporting concentrations of 4.49-14.76/ mg/g dry seed depending on genotype and analytical method (Nandan *et al.*, 2024). Phytic acid, another major antinutrient, is typically found in the range of 10.5-13.5/ g/kg seed dry weight (~1.05-1.35/ %) (Singhania *et al.*, 2023). In amaranth, saponins occur at much lower levels (0.9-4.91/ mg/kg grain), while phytic acid content is often reported as 2.9-7.9/ g/kg

seed dry weight (0.29-0.79/ %) (Prajapati and Singh, 2024; Singhania *et al.*, 2023). Buckwheat differs in antinutrient profile: although phytic acid content can be high in unprocessed seed fractions (~6-18/ %), fagopyrins (phototoxic naphthodianthrone compounds) are mainly present in vegetative tissues and hulls rather than edible dehulled seeds, with leaf/green tissue containing 0.322-2.3/ mg/g fagopyrin (Sofi *et al.*, 2023). These values indicate that quinoa generally has the highest saponin burden, amaranth has moderate phytate levels with low saponins, and buckwheat is notable for fagopyrins in non-seed tissues while dehulled seeds have significantly reduced antinutrient content. Human exposure to antinutrients in

Pseudocereals is generally safe under typical dietary consumption but can pose risks at high intake or without proper processing. In quinoa (*C. quinoa*), saponins at levels in commercially cleaned “sweet” varieties (<0.11/ %) are safe, though higher intakes in animal studies (~50/ mg/kg body weight/day) can cause mild mucosal irritation and gut alterations (Zhang *et al.*, 2024). Phytic acid in quinoa and amaranth (2.9-13.5 g/kg) can reduce mineral (Fe, Zn, Ca, Mg) absorption if intake exceeds ~200-400 mg per meal, particularly in at-risk groups, but effects are mitigated in balanced diets through phytase activity (López-Moreno *et al.*, 2022; Petroski and Minich, 2020). In Buckwheat, fagopyrins (mainly in leaves and hulls) can cause photosensitivity, while dehulled groats and flour have very low levels and are safe when processed (Sofi *et al.*, 2023). Proper processing such as washing, dehulling, cooking, soaking, germination, and fermentation effectively lowers antinutrient levels and enhances nutrient bioavailability (Petroski and Minich, 2020).

Effective processing markedly reduces antinutritional factors in Pseudocereals. For quinoa, washing, de saponification, and pearling remove surface saponins (>90/ %), while boiling further leaches them into cooking water (Martínez-Villaluenga *et al.*, 2020). Soaking, germination, and lactic acid fermentation reduce phytic acid (17-75/ %) and enhance mineral bioavailability (Valenzuela Zamudio and Segura Campos, 2022). For amaranth, low saponin content means washing and cooking suffice for safety, while soaking and germination reduce phytic acid and tannins and improve nutrient content (Prajapati and Singh, 2024). In Buckwheat, dehulling removes hull-associated ANFs, and soaking and germination lower phytic acid and tannins and enhance antioxidant activity (Sofi *et al.*, 2023). Combining these treatments is most effective for reducing ANFs while maintaining nutritional quality.

The main toxicological concerns in Pseudocereals relate to naturally occurring antinutrients, all of which are considered safe when standard processing is followed. In quinoa, triterpenoid saponins in the seed coat can cause gastrointestinal irritation at high intake, so commercial standards require washing or de-saponification to reduce levels below ~0.1% (El Hazzam *et al.*, 2020). Amaranth contains low saponins but relatively higher phytates and oxalates, which impair mineral absorption but do not pose direct toxicity risks at normal dietary levels; cooking and germination substantially reduce them (Nandan *et al.*, 2024). Buckwheat uniquely contains fagopyrins, photosensitizing compounds found mainly in leaves and flowers that can cause fagopyrism if consumed in large amounts, though dehulled groats and flour contain negligible levels and are considered safe (Sofi *et al.*, 2023). Overall, regulatory bodies (Codex/EFSA) classify all three Pseudocereals as safe foods when properly processed.

## 8. Challenges in Pseudocereals cultivation

Pseudocereal production is challenged by factors that reduce efficiency and yield stability, often resulting in low outputs of 1-1.5 t ha<sup>-1</sup> (Malik and Singh, 2022). Key issues include a narrow genetic base, absence of stress-tolerant and high-yield cultivars, and limited agronomic knowledge on critical practices (Singhania *et al.*, 2023). Seed-related problems like asynchronous maturity and high shattering rates complicate harvesting (Pirzadah and Malik, 2020). Genetic progress is hindered by factors such as heteromorphic self-incompatibility in buckwheat and insufficient mutagenesis and genome-editing technologies (Mukhtar *et al.*, 2021).

Pseudocereals grown on marginal lands face drought, salinity, heat, frost, and nutrient-deficient soils, which contribute to oxidative stress and reduced photosynthesis (Nagaraja *et al.*, 2024). The absence of standardized preprocessing methods for antinutritional factors restricts market expansion, compounded by low consumer awareness, limited gluten-free options, inconsistent processing quality, and inadequate research into their functional properties (Zhang *et al.*, 2024). Commercialization hurdles include poor value-chain integration and weak connections between farmers and industries, while institutional barriers such as low policy support and insufficient funding further impede crop breeding and adoption (Singhania *et al.*, 2023). Socio-economic issues such as labour shortages, farmer migration, and limited extension services add to these constraints (Singhania *et al.*, 2023). Despite these barriers, Pseudocereals hold significant potential due to their nutrient richness and climate resilience.

## 9. Future perspectives

Advancements in pseudocereal cultivation leverage genomic tools like genotyping-by-sequencing (GBS) and RAD-seq to enhance genetic diversity and identify crucial allelic variations (Malik and Singh, 2022). Whole-genome resequencing and pan-genome analyses help characterize gene families related to stress tolerance and grain quality (Zhang *et al.*, 2024). Including crop wild relatives can introduce vital drought- and salinity-tolerance alleles in species like quinoa and amaranth (Repo-Carrasco-Valencia and Vidaurre-Ruiz, 2022). High-quality genomic resources such as the chromosome-scale *C. quinoa* reference genome by Rey and Jarvis (2021) now provide powerful tools for gene family analysis, GWAS anchoring and comparative studies within the Chenopodium lineage. Similarly, the draft and Hi-C-guided chromosome assemblies for *A. hypochondriacus* enable candidate-gene discovery for nutritional traits and deeper comparative genomics with both cultivated and weedy *Amaranthus* species (Blair *et al.*, 2023). In Buckwheat, the availability of early draft genomes alongside recent chromosome-level assemblies for *F. esculentum* and *F. tataricum* supports advanced exploration of flavonoid and rutin biosynthesis through expression atlases and pathway mapping (Zargar *et al.*, 2024). Together, these crop-specific genomic datasets lay the foundation for future work integrating multi-omics, refining metabolic pathway reconstruction and accelerating breeding strategies aimed at enhancing the nutritional quality of Pseudocereals.

Precision genome-editing technologies, such as CRISPR/Cas9, facilitate targeted gene modifications linked to seed shattering and abiotic stress regulators such as DREB, HSP, and NAC transcription factors (Pirzadah and Malik, 2020). Recent CRISPR Cas9 studies in quinoa have successfully enhanced seed nutritional traits such as lysine, zinc, and vitamins without affecting yield (Rey and Jarvis, 2021). While direct genome editing in amaranth and Buckwheat is limited, CRISPR workflows established in rice and wheat can be adapted to these Pseudocereals. High-throughput phenotyping platforms integrating imaging, sensors, and analytics are essential for efficiently linking edits to observable traits (Gill *et al.*, 2022). Global pseudocereal breeding programs leverage participatory and pre-breeding strategies to enhance agronomic performance, abiotic stress resilience, and nutritional biofortification. Quinoa improvement has been facilitated through the Worldwide Consortium on Evolutionary Participatory Breeding, enabling targeted selection for climate-resilient, nutrient-dense genotypes while maintaining genetic diversity

(Rey and Jarvis, 2021). Population structure analyses and core germplasm construction in Tartary Buckwheat demonstrate significant genetic variation among wild, landrace, and improved accessions, underpinning genetic conservation and targeted selection for quality and stress resilience traits (Cheng *et al.*, 2025). In amaranth, systematic utilization of *ex situ* germplasm collections and core set characterization supports marker-assisted selection and the identification of elite lines for high-protein content, seed morphological traits, and abiotic stress tolerance (Nagaraja *et al.*, 2024).

Agronomic advancements require standardized production methods supported by precision agriculture, with practices like drip irrigation enhancing water-use efficiency (G20 AWG, 2023). Moreover, adjustments in planting density and nitrogen fertilization stabilize yields amid climate variations (Repo-Carrasco-Valencia and Vidaurre-Ruiz, 2022). Innovations such as mini-combines tackle labor shortages and support community seed banks for consistent seed quality (Malik and Singh, 2022). Nutritional enhancement techniques like de-saponification and germination improve quinoa's acceptability and mineral bioavailability, aligning with market growth for gluten-free and ready-to-eat foods (Zhang *et al.*, 2024).

Strengthening pseudocereal value chains involves investing in processing centers, aggregation systems, and cold-chain logistics to minimize post-harvest losses (Nagaraja *et al.*, 2024). Implementing traceability technologies like blockchain and acquiring certifications (organic, GI, gluten-free) can enhance market visibility. Improved consumer acceptance can be achieved through targeted awareness and effective branding (Zhang *et al.*, 2024). Policy interventions, including integration into national food initiatives and supportive measures like processing facility subsidies and increased research investment, are crucial (Nagaraja *et al.*, 2024). Educational efforts through farmer field schools and digital platforms will accelerate knowledge sharing (Malik and Singh, 2022). Coordinated advancements in breeding, agronomy, processing, and value-chain development can position Pseudocereals as climate-resilient staples.

## 10. Conclusion

Pseudocereals have emerged as essential contributors to sustainable food systems and global nutritional security because of the exceptional dietary value, rich bioactive composition, and diverse utility in food and industrial uses. Their nutritionally rich protein fractions, dietary fiber, unsaturated lipids, and health-promoting constituents such as fagopyritols, flavonols, saponins, squalene, and phytosterols position amaranth, quinoa, Buckwheat, and chia as strong alternatives to traditional cereals, particularly for gluten-free and allergen-friendly diets. These crops demonstrate significant potential in the development of functional foods, nutraceuticals, and pharmaceutical products, although consumer awareness and global utilization remain limited by production costs and restricted cultivation regions. Extensive research highlights the presence of bioactive peptides and protein hydrolysates with antioxidant, antihypertensive, anti-inflammatory, antimicrobial, hypocholesterolemic, and antitumor properties, yet further *in vivo* studies and clinical trials are needed to confirm their mechanisms and health benefits. Overall, the nutritional superiority, adaptability, and resilience of Pseudocereals underline their value in meeting contemporary dietary challenges, improving public health, and supporting future advancements in agriculture, food innovation, and global food security.

## Conflict of interest

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

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