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Sustainable grains for gluten-free diets: the potential of millets and pseudocereals in alleviating gluten-related disorders

Amisha Kaushik and Sukhcharn Singh *

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The increasing prevalence of gluten-related disorders (GRDs) has increased the demand for nutritionally balanced gluten-free diets. However, conventional gluten-free products are often associated with poor nutritional quality and micronutrient deficiencies. This review highlights millets and pseudocereals as sustainable, nutrient-dense alternatives for gluten-free food systems. These naturally gluten-free grains are rich in high-quality proteins, dietary fiber, resistant starch, and essential minerals such as iron, calcium, magnesium, and zinc. They also contain bioactive compounds, including phenolics, flavonoids, phytosterols, and antioxidant peptides, associated with antioxidant, anti-inflammatory, and cardioprotective effects. Their adaptability to marginal agro-climatic conditions and low-input cultivation further supports environmental sustainability and food security. Moreover, processing techniques such as germination, fermentation, soaking, and extrusion enhance nutrient bioavailability and reduce antinutritional factors. Overall, millets and pseudocereals represent promising sustainable grain alternatives for improving gluten-free nutrition and health outcomes in individuals with GRDs.

Sustainability spotlight

The manuscript presents a thorough study on the integration of millets and pseudocereals into gluten-free food systems, representing a transformative approach to sustainable nutrition and climate-resilient agriculture. These ancient grains, naturally gluten-free and nutritionally superior, thrive in marginal soils with minimal water and fertilizer inputs. By utilizing innovative processing techniques such as fermentation, germination, and extrusion, their nutritional potential can be further optimized, leading to the creation of gluten-free products that are both health-promoting and eco-friendly. Embracing millets and pseudocereals thus aligns with global sustainability goals by fostering food security, reducing dependency on resource-intensive crops, and promoting resilient, climate-smart dietary solutions for future generations. Their integration into food systems aligns with efforts to achieve several United Nations Sustainable Development Goals (SDGs).

1 Introduction

There is a persistent rise in the demand for food production to meet the needs of the growing global population. The primary staples in the diets of people worldwide include cereals such as rice, corn, and wheat. However, alongside the increasing need for these cereals, food sensitivities have also been on the rise over the past few decades. The predominant factor contributing to these food sensitivities is the presence of gluten.[1] Gluten, composed of glutenin and gliadin, shows high genetic variability. Gliadin, rich in proline and glutamine, is resistant to digestion, as its compact structure prevents enzymatic breakdown. This resistance allows gliadin to persist in the digestive system, triggering immune responses in individuals with gluten-related disorders.[2]

Gluten-related disorders (GRDs) comprise a set of immune-mediated conditions associated with gluten intolerance. Gluten, a structural protein in wheat and related grains can elicit immune responses in genetically predisposed individuals. Gluten-related disorders (GRDs) encompass autoimmune conditions (*e.g.*, celiac disease), wheat allergy, and non-celiac gluten sensitivity.[3] At present, the sole established and safe therapy for GRDs is adherence to a gluten-free diet (GFD). This dietary regimen involves avoiding foods containing wheat, rye, barley, and their derivatives, and in certain instances, oats. For individuals affected by gluten-related disorders (GRDs), dietary management must not only exclude gluten but also ensure adequate nutrition and energy intake, thereby significantly impacting overall health.[4] An imbalanced gluten-free diet (GFD) can lead to metabolic disturbances and nutrient deficiencies. Inadequate guidance on food choices and healthy eating may exacerbate these issues, as gluten-free products often contain higher levels of lipids and refined starches to compensate for the absence of gluten.[5] Moreover, gluten-free foods are typically

Sant Longowal Institute of Engineering and Technology, Punjab, India. E-mail: amishakaushik267@gmail.com; sukhcharns@yahoo.com

more expensive and may have lower nutritional and sensory quality. Social challenges arise from limited access to the same food options as individuals without gluten-related disorders (GRDs), including difficulties in finding and accessing safe gluten-free foods and suitable food services.[6]

With the increasing demand for gluten-free (GF) products, there has been a corresponding rise in research focused on various types of GF cereals, examining aspects such as their nutritional composition, digestibility, and potential applications.[7] Gluten-free cereals (GFCs) are grains that either lack gluten or contain it in amounts below 20 parts per million (ppm). Examples include sorghum, millets, and pseudocereals. These grains are crucial for individuals with gluten-related disorders, who must avoid prolamine-containing grains like barley, wheat, and rye, as these can cause severe intestinal damage.[8] The rising consumption of gluten-free cereals (GFCs) is driven by the growing prevalence of gluten-related disorders and the popularity of gluten-free diets among healthy individuals. However, gluten-free foods often contain higher levels of fat, sugar, and sodium, while being lower in protein, minerals, and dietary fiber, impacting their overall nutritional balance.[7]

Millets and pseudocereals, including amaranths, buckwheat, and chenopods, are notable for their adaptability to diverse growing conditions and their higher nutrient profiles compared to gluten-containing grains. They thrive in short growing seasons, resist drought and disease, and are essential in hill farming systems. Their resilience and nutritional advantages make them valuable as climate change affects agriculture and food production.[9] Some gluten-free (GF) grains contain anti-nutritional factors, but these can be reduced through processing. These grains are also rich in phytochemicals, boosting their nutritional value. Recently, gluten-free grains and pseudocereals such as quinoa, millet, sorghum, teff, amaranth, and buckwheat have been explored for developing gluten-free products, including bread, pasta, breakfast cereals, and puffed or extruded snacks. These grains often offer comparable or superior nutrient profiles compared to traditional gluten-containing grains like wheat and barley.[10]

Despite the expanding literature on gluten-free grains, existing reviews have largely addressed millets and pseudocereals in a fragmented manner, focusing separately on their nutritional composition, health benefits, processing behavior, or product applications. For example, Martínez-Villaluenga *et al.*[7] reviewed the nutritional value and applications of pseudocereals in gluten-free foods, while Thakur *et al.*[14] emphasized processing-induced changes in pseudocereals. Similarly, Marciniak *et al.*[5] highlighted the nutritional limitations of conventional gluten-free diets, particularly their dependence on refined starches and associated metabolic concerns. However, these studies do not fully integrate the dietary requirements of gluten-related disorders (GRDs) with the nutritional advantages, antinutrient challenges, processing strategies, sustainability indicators, consumer acceptance, and commercialization potential of millets and pseudocereals within a single framework.

In this context, the present review addresses this gap by integrating multiple dimensions: (i) the dietary relevance of gluten-free grains in GRD management and associated nutritional imbalances, including low fiber intake, mineral deficiencies, anemia, and bone-health concerns; (ii) the nutritional and bioactive potential of millets and pseudocereals, including high-quality proteins, dietary fiber, resistant starch, minerals, phenolics, and antioxidant compounds; (iii) the role of processing methods such as soaking, germination, fermentation, dehulling, extrusion, puffing, and popping in reducing antinutritional factors, enhancing nutrient bioavailability, and improving sensory and technological quality; and (iv) their application in gluten-free bakery products, pasta, beverages, snacks, and infant foods. Additionally, this review incorporates sustainability and market-oriented perspectives by considering measurable environmental indicators, low-input cultivation, climate resilience, consumer perception, adoption barriers, and industrial-scale feasibility. By consolidating these interconnected aspects, this review provides a comprehensive and application-oriented perspective on millets and pseudocereals as nutrient-dense, sustainable, and technologically relevant alternatives for improving gluten-free food systems.

2 Methodology/search strategy

This review was prepared using a structured literature-search strategy to identify, analyse, and synthesize published studies related to gluten-related disorders, gluten-free diets, millets, pseudocereals, nutritional composition, processing methods, product development, and sustainability indicators. The search was conducted using major academic databases, including Google Scholar, ScienceDirect, PubMed, Scopus, Web of Science, SpringerLink, Wiley Online Library, Taylor & Francis Online, MDPI, and Crossref. Keywords were used individually and in combination with Boolean operators such as “AND” and “OR”. The main search terms included “gluten-related disorders”, “celiac disease”, “non-celiac gluten sensitivity”, “wheat allergy”, “gluten-free diet”, “millets”, “pseudocereals”, “quinoa”, “amaranth”, “buckwheat”, “sorghum”, “pearl millet”, “finger millet”, “nutritional composition”, “bioactive compounds”, “antinutritional factors”, “processing techniques”, “germination”, “fermentation”, “soaking”, “puffing”, “gluten-free bakery products”, “gluten-free pasta”, “gluten-free beverages”, “sustainable grains”, “carbon footprint”, “water footprint”, and “carbon sequestration”.

Articles published mainly between 2015 and 2025 were prioritized to ensure updated coverage; however, older studies were included when they provided foundational information, classical disease mechanisms, standard definitions, or historically important evidence. For example, older studies related to gluten immunopathology, dermatitis herpetiformis, and disease classification were retained where they remained scientifically relevant. Peer-reviewed original research articles, review articles, clinical studies, food-processing studies, life-cycle assessment studies, and authoritative reports were considered. Studies were included when they directly addressed gluten-related disorders, the nutritional or functional properties of millets and pseudocereals, processing effects, gluten-free product development, or sustainability indicators relevant to

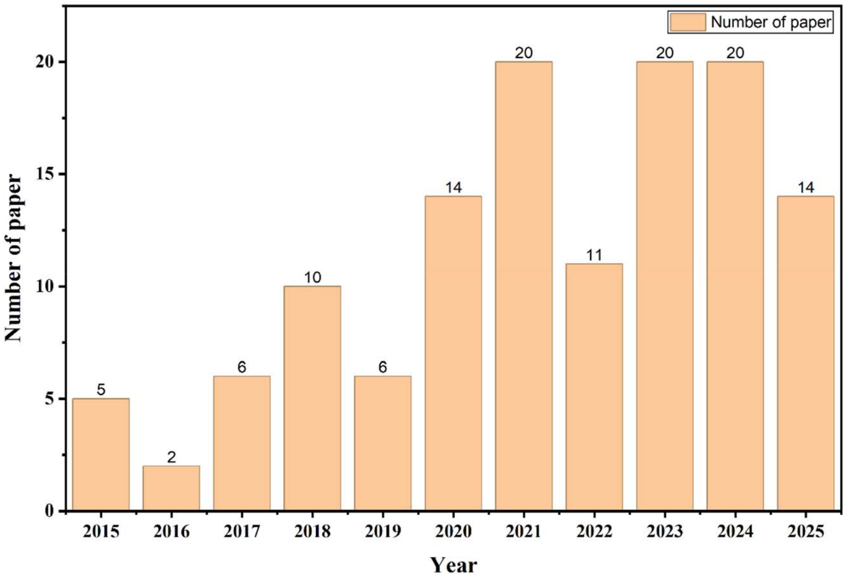


Fig. 1 Publication year distribution of studies included in the review.

these grains. Studies were excluded if they were unrelated to gluten-free diets, focused on non-food uses of grains, lacked sufficient methodological or compositional detail, were not available in English, or were editorials, opinion pieces, blogs, non-peer-reviewed web articles, presentation slides, or duplicate records.

The selected literature was screened first by title and abstract, followed by full-text assessment for relevance to the scope of the review. Priority was given to recent, peer-reviewed, and high-quality studies, while older references were used only where they supported established concepts or classical mechanisms. The extracted information was organized thematically into sections covering gluten-related disorders, nutritional composition, antinutritional challenges, processing strategies, gluten-free product applications, and sustainability indicators. As this article is a narrative review with a structured search strategy rather than a meta-analysis, quantitative pooling and formal risk-of-bias assessment were not performed. The publication year distribution of studies included in the review is presented in Fig. 1, while the inclusion and exclusion criteria used for literature selection are summarized in Tables 1 and 2.

Table 1 Databases and search platforms used for literature collection

Sr no.	Database/platform	Website
1	Google Scholar	https://scholar.google.com/
2	ScienceDirect	https://www.sciencedirect.com/
3	PubMed	https://pubmed.ncbi.nlm.nih.gov/
4	Scopus	https://www.scopus.com/
5	Web of Science	https://www.webofscience.com/
6	SpringerLink	https://link.springer.com/
7	Wiley Online Library	https://onlinelibrary.wiley.com/
8	Taylor & Francis Online	https://www.tandfonline.com/
9	MDPI	https://www.mdpi.com/
10	Crossref	https://search.crossref.org/

3 Dietary gluten: a trigger for gluten-related disorders

According to the Codex Alimentarius Standard for Foods for Special Dietary Use for Persons Intolerant to Gluten (CXS 118-1979; adopted in 1979, revised in 2008, and amended in 1983 and 2015), gluten is defined as the protein fraction from wheat, rye, barley, oats, or their crossbred varieties and derivatives, to which some individuals are intolerant, and which is insoluble in water and 0.5 M NaCl. The standard further defines prolamins as the gluten fraction extractable in 40–70% ethanol, including gliadin from wheat, secalin from rye, hordein from barley, and avenin from oats. The prolamin content of gluten is generally considered to be approximately 50%. Foods labelled as "gluten-free" should not contain more than 20 mg kg^{-1} gluten, while specially processed foods with reduced gluten content may contain more than 20 mg kg^{-1} but not more than 100 mg kg^{-1}, depending on national regulations.[15] Fig. 2 summarizes the taxonomic classification and gluten protein composition of harmful and non-harmful cereals for individuals with gluten-related disorders.

Gluten represents the major storage protein fraction of wheat and related cereals and is mainly composed of gliadins and glutenins, both characterized by high levels of glutamine and proline.[2,16] The specific prolamins in gluten-containing cereals include gliadin in wheat, secalin in rye, and hordein in barley, whereas oats contain avenin, a related prolamin that is generally considered less immunogenic for most individuals with coeliac disease, although oat safety depends on cultivar purity and avoidance of contamination with wheat, barley, or rye.[17] Gliadins are alcohol-soluble monomeric proteins classified into α-, β-, γ-, and ω-types, whereas glutenins are alcohol-insoluble polymeric proteins linked by interchain disulfide

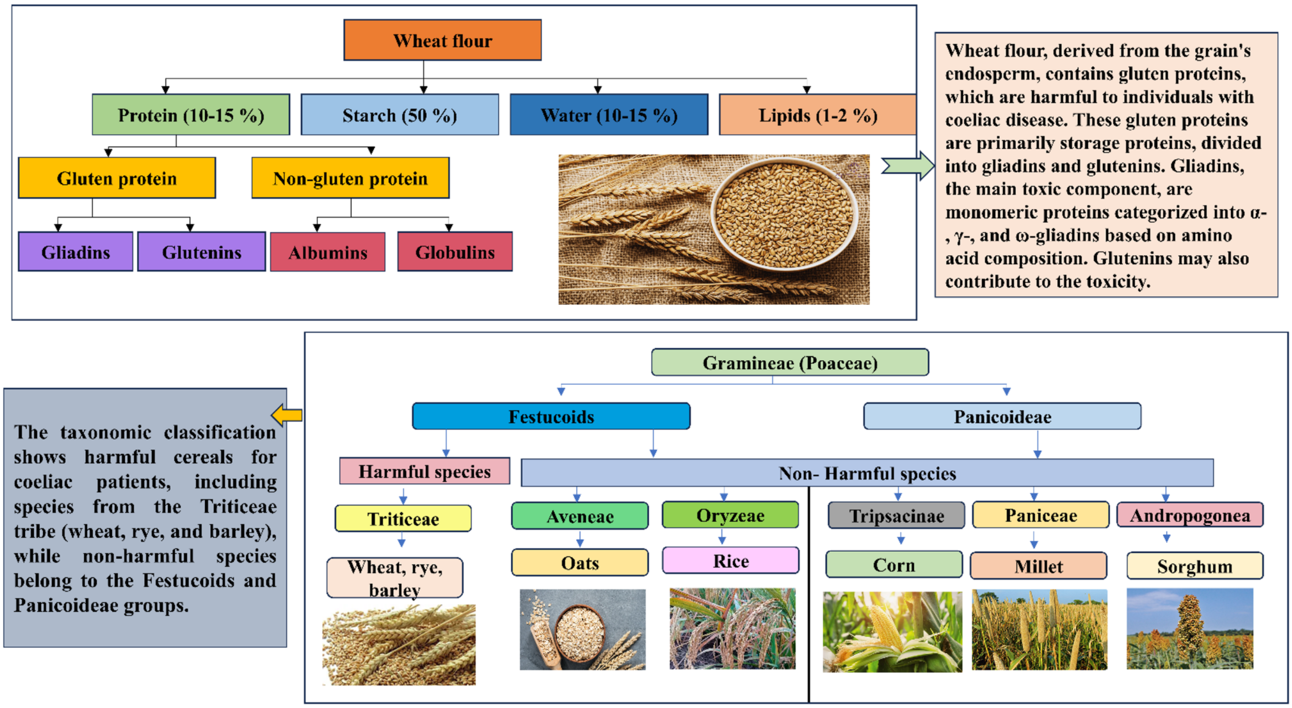
Table 2 Inclusion and exclusion criteria used for literature selection

Inclusion criteria	Exclusion criteria
Studies focused on gluten-related disorders, including celiac disease, wheat allergy, dermatitis herpetiformis, gluten ataxia, and non-celiac gluten sensitivity	Studies unrelated to gluten-related disorders or gluten-free diets
Studies reporting nutritional composition, bioactive compounds, antinutritional factors, or functional properties of millets and pseudocereals	Studies focused only on unrelated crops, non-food applications, or non-dietary uses
Studies on processing methods such as soaking, germination, fermentation, milling, puffing, extrusion, and their effects on nutritional quality	Studies lacking sufficient methodological, nutritional, or processing details
Studies on gluten-free product development, including bakery products, pasta, noodles, beverages, snacks, and infant foods	Editorials, blogs, opinion articles, presentation slides, keynote summaries, and non-peer-reviewed sources
Studies reporting sustainability indicators such as carbon footprint, water footprint, input requirement, climate resilience, or carbon sequestration	Duplicate records, inaccessible full texts, or studies with insufficient extractable data
Peer-reviewed original articles, review articles, clinical studies, food-processing studies, LCA studies, books, and authoritative reports	Non-English articles without available translation
Mostly studies published from 2015–2025, with older studies retained only when foundational or mechanistically important	Older studies not providing foundational, classical, or still-relevant evidence

bonds and divided into high- and low-molecular-weight glutenin subunits.[16,18]

During dough preparation, gluten develops when wheat flour is hydrated and mechanically mixed, allowing gliadin and glutenin proteins to interact through disulfide bonding, hydrogen bonding, and hydrophobic interactions to form a continuous viscoelastic network.[18,19] Gliadins mainly contribute dough extensibility and viscosity, while glutenins provide elasticity and dough strength.[2,18] This gluten network is responsible for the characteristic technological properties of wheat-based bakery and pasta products, including water absorption, cohesiveness, gas retention, loaf volume, elasticity, pasta firmness, cooking tolerance, and structural integrity.[2,20]

Therefore, removing gluten creates major technological challenges in gluten-free formulations, including weak dough structure, poor gas retention, crumb fragility, reduced elasticity, higher cooking loss, and inferior texture.[20,21] Although millets and pseudocereals are naturally gluten-free and nutritionally



Wheat flour, derived from the grain's endosperm, contains gluten proteins, which are harmful to individuals with coeliac disease. These gluten proteins are primarily storage proteins, divided into gliadins and glutenins. Gliadins, the main toxic component, are monomeric proteins categorized into α-, γ-, and ω-gliadins based on amino acid composition. Glutenins may also contribute to the toxicity.

The taxonomic classification shows harmful cereals for coeliac patients, including species from the Triticeae tribe (wheat, rye, and barley), while non-harmful species belong to the Festucoids and Panicoideae groups.

Fig. 2 Taxonomic classification and gluten protein composition of harmful and non harmful cereals for gluten-related disorders.

valuable, they lack gluten-forming proteins and therefore require appropriate formulation and processing strategies. Blending with other gluten-free flours or starches, hydrocolloids, proteins, enzymes, emulsifiers, sourdough fermentation, and extrusion are commonly used to improve structure, texture, and product acceptability in millet- and pseudocereal-based gluten-free foods.[11]

4 Gluten-induced disorders: insights into pathophysiology and treatment

GRDs are categorized into three primary groups based on their pathological mechanisms: autoimmune conditions such as coeliac disease, dermatitis herpetiformis, and gluten ataxia; allergic conditions like wheat allergy; and non-autoimmune-allergic conditions such as non-celiac gluten sensitivity. Each disorder presents specific intestinal and/or extraintestinal symptoms that improve upon gluten elimination (Fig. 3). Additionally, the pathway of gluten-induced immune response associated with celiac disease, gluten allergy, and dermatitis herpetiformis is illustrated in Fig. 4.[3]

4.1 Coeliac disease

Coeliac disease is a chronic immune-mediated enteropathy triggered by dietary gluten in genetically susceptible individuals and is predominantly associated with HLA-DQ2 and/or HLA-DQ8 haplotypes. However, genetic predisposition alone is insufficient for disease development, suggesting the involvement of additional environmental, immunological, and dietary factors. The disorder is reported more frequently in females and may develop at any stage of life after the introduction of gluten-containing foods.[17,22] Gluten exposure primarily affects the small intestinal mucosa, leading to villous atrophy, crypt hyperplasia, impaired nutrient absorption, and variable gastrointestinal or extraintestinal manifestations; however, some individuals may remain clinically asymptomatic.[23]

The pathophysiological relevance of gluten in coeliac disease is associated with the structural resistance of gliadin and glutenin proteins to complete enzymatic digestion. These proteins are rich in proline and glutamine residues, which limits their hydrolysis by gastric, pancreatic, and intestinal enzymes. Consequently, partially digested immunogenic gluten peptides may persist in the intestinal lumen and cross the epithelial barrier through transcellular or paracellular routes into the lamina propria, where they contribute to immune-mediated mucosal injury.[24] From a dietary perspective, strict lifelong adherence to a gluten-free diet remains the only established treatment for coeliac disease. Therefore, the formulation of nutritionally adequate gluten-free foods is essential, as many conventional gluten-free products rely heavily on refined starches and may provide lower amounts of protein, dietary fiber, minerals, and bioactive compounds.[5,7]

4.2 Dermatitis herpetiformis

Dermatitis herpetiformis is a chronic autoimmune blistering disorder influenced by gluten and is considered an extra-intestinal cutaneous manifestation of coeliac disease. It is characterized by intensely pruritic, symmetrical, and polymorphic skin lesions, commonly affecting the extensor surfaces of the elbows and knees, buttocks, and sacral region.[25] These lesions may appear as grouped erythematous papules, urticarial plaques, or vesicles and can heal with post-inflammatory pigmentation changes. Histologically, dermatitis herpetiformis is associated with neutrophilic infiltration and granular IgA deposits at the dermal–epidermal junction, while diagnosis

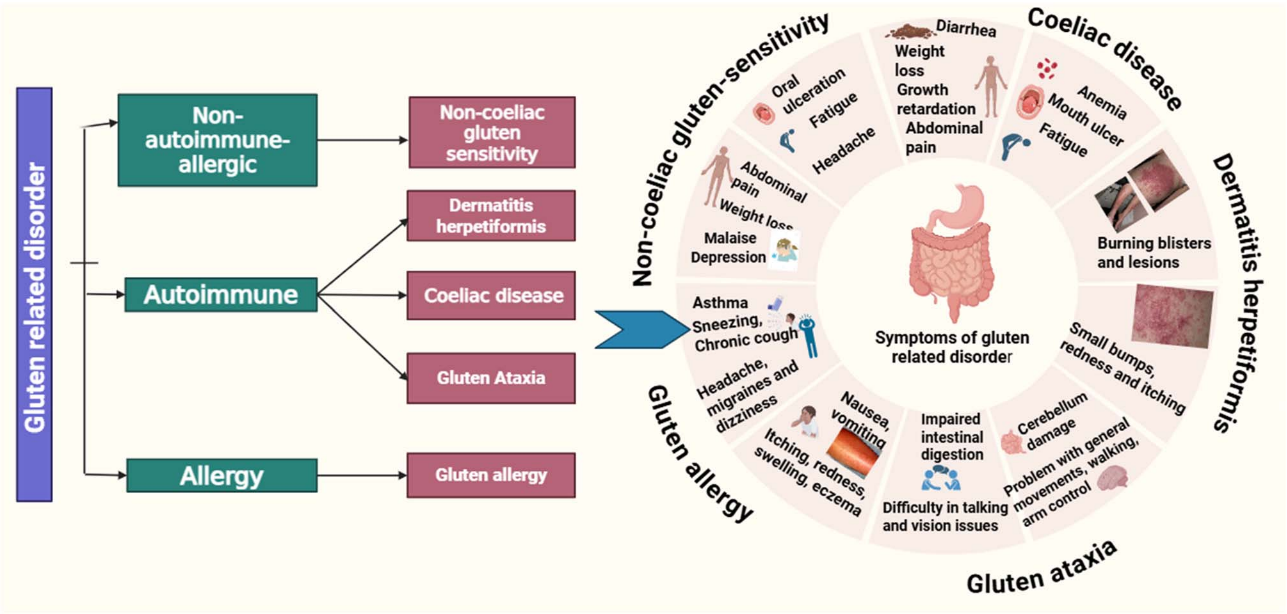


Fig. 3 Gluten-related disorders: classification and symptoms.

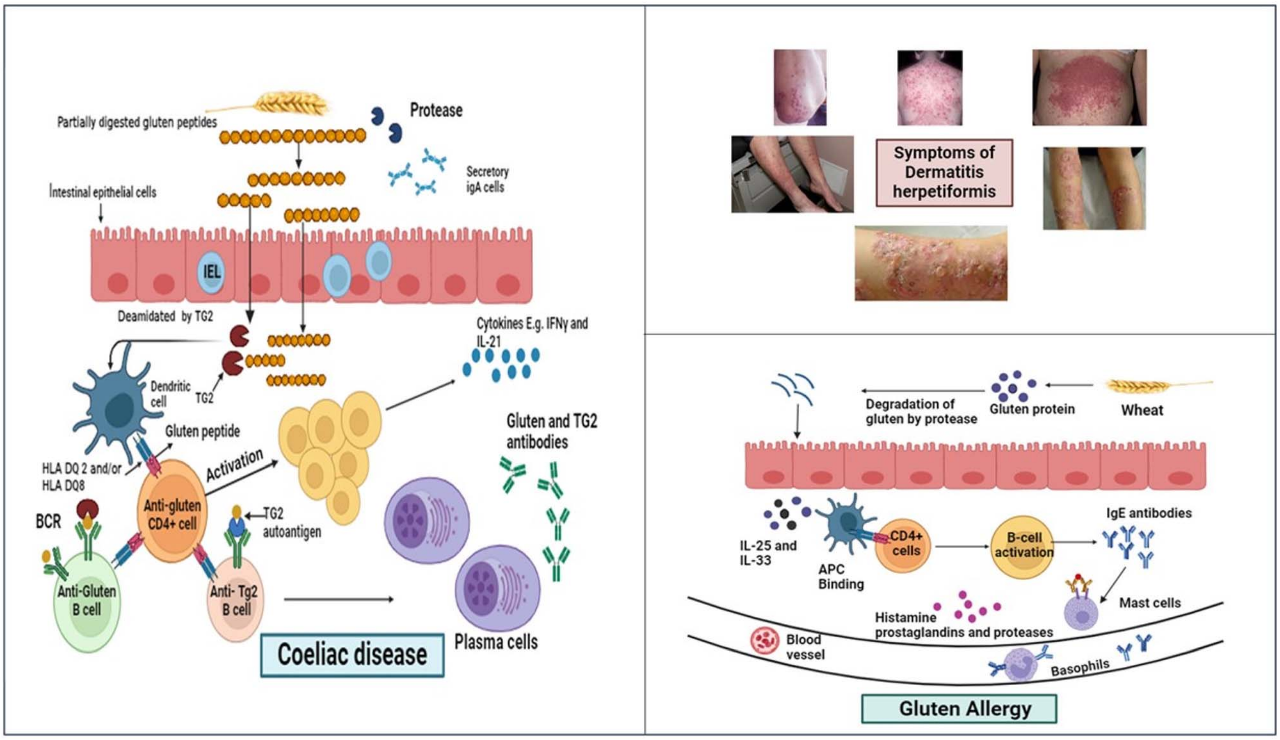


Fig. 4 Pathway of gluten-induced immune response in celiac disease, gluten allergy and symptoms of dermatitis herpetiformis.

is commonly supported by the presence of granular IgA and transglutaminase 3 deposits in the papillary dermis.[26,27]

The pathophysiological relevance of gluten in dermatitis herpetiformis is linked to gluten-dependent autoantibody production, particularly against epidermal transglutaminase/transglutaminase 3. The condition is frequently associated with prolonged gluten exposure and untreated coeliac disease, supporting the gut–skin connection in gluten-related autoimmunity.[28] Although the precise mechanisms underlying autoantibody formation and lesion development remain incompletely understood, dietary gluten withdrawal plays a central role in disease management. Therefore, long-term adherence to a gluten-free diet is essential for controlling symptoms and reducing disease activity, highlighting the importance of safe and nutritionally adequate gluten-free foods for affected individuals.

4.3 Gluten ataxia

Gluten ataxia is an immune-mediated neurological manifestation associated with gluten sensitivity and is primarily characterized by progressive cerebellar dysfunction. It commonly presents with gait instability, impaired coordination, dysarthria, dysphonia, abnormal eye movements, and, in some cases, peripheral neuropathy that may precede gastrointestinal symptoms.[29] The condition usually develops gradually, often around mid-to-late adulthood, and may also be associated with mild cognitive symptoms such as impaired concentration, memory disturbances, and “brain fog,” which can improve following dietary modification.[30–32]

The pathophysiological relevance of gluten in gluten ataxia is linked to immune-mediated neurological injury, although the exact mechanism remains incompletely understood. Proposed mechanisms include gluten-triggered immune responses, cross-reactivity between gluten-related antibodies and cerebellar structures such as Purkinje cells, and neurological effects associated with nutrient deficiencies or metabolic disturbances in gluten-related disorders.[31,33] From a dietary perspective, gluten restriction is considered an important management strategy in gluten-associated neurological manifestations. Therefore, maintaining long-term dietary adherence requires gluten-free foods that are not only safe but also nutritionally adequate, particularly because neurological manifestations may coexist with malabsorption-related deficiencies.

4.4 Wheat allergy

Wheat allergy is an immune-mediated adverse reaction to wheat proteins that may occur following ingestion, inhalation, or occupational exposure to wheat flour. Wheat proteins include albumins, globulins, gliadins, and glutenins, all of which may contribute to allergic responses depending on the route of exposure and individual sensitivity.[34] Among these, gliadins and glutenins are important allergenic fractions, while ω-5 gliadin is particularly associated with wheat-dependent exercise-induced anaphylaxis. Soluble wheat proteins, especially albumins and globulins, are frequently implicated in respiratory allergy such as baker's asthma.[35,36]

The clinical manifestations of wheat allergy vary from mild to severe and may include cutaneous, gastrointestinal, respiratory, or systemic symptoms such as urticaria, eczema, abdominal discomfort, rhinitis, asthma, and anaphylaxis.[37] Unlike coeliac disease, wheat allergy is generally associated with IgE-mediated hypersensitivity and does not necessarily involve autoimmune intestinal damage. In children, symptoms may appear after the introduction of wheat-containing foods, whereas in adults wheat allergy is less common but may present as wheat-dependent exercise-induced anaphylaxis.[38,39] From a dietary perspective, the major management strategy is avoidance of wheat and wheat-derived ingredients, along with careful control of cross-contamination during food processing. This makes wheat-free and gluten-free product development highly relevant for affected consumers.

4.5 Non-coeliac gluten sensitivity

Non-celiac gluten sensitivity (NCGS) is characterized by the development of gastrointestinal and extraintestinal symptoms following the ingestion of gluten- or wheat-containing foods in individuals who do not meet the diagnostic criteria for coeliac disease or wheat allergy. Unlike coeliac disease, NCGS is not associated with IgA anti-tissue transglutaminase autoantibodies, and unlike wheat allergy, it does not involve specific IgE-mediated responses to wheat proteins.[37,40] Symptoms usually appear within hours to days after gluten or wheat consumption and may include abdominal distension, abdominal pain, diarrhea, flatulence, headache, fatigue, musculoskeletal discomfort, and skin-related manifestations such as eczema.[41]

The pathophysiological relevance of gluten in NCGS remains incompletely defined and continues to be debated because of its clinical overlap with irritable bowel syndrome and other functional gastrointestinal disorders.[42] Although gluten has been implicated in symptom development, other wheat-related components, including amylase/trypsin inhibitors and fermentable oligo-, di-, monosaccharides and polyols, may also contribute to symptom induction through innate immune activation or fermentative effects in the intestine.[43,44] From a dietary perspective, symptom management commonly involves reduction or exclusion of gluten- and wheat-containing foods; however, the broader involvement of wheat components highlights the need for well-formulated gluten-free products with improved nutritional quality, digestibility, and consumer acceptability.

5 Gluten-free diet redefined: the role of millets and pseudocereals in managing gluten sensitivities

A gluten-free diet is the primary dietary strategy for individuals with gluten-related disorders; however, long-term dependence on poorly formulated gluten-free products may contribute to nutritional imbalances. Many commercial gluten-free foods are based on refined rice, maize, potato, or tapioca starches and may contain lower levels of protein, dietary fiber, minerals, and bioactive compounds, while sometimes containing higher amounts of sugars and fats. Such dietary patterns may increase the risk of obesity, metabolic disorders, and other chronic diseases if not carefully managed.[8,45] Therefore, the selection of gluten-free ingredients with low glycemic response, balanced macronutrient composition, and higher micronutrient and bioactive content is important for improving the quality of gluten-free diets.

A wide range of ingredients can be used as alternatives to wheat and other gluten-containing cereals, including rice, maize, sorghum, teff, oats, legumes, tuber flours, starches, millets, and pseudocereals such as quinoa, amaranth, and buckwheat. Rice and maize are widely used because of their availability and processing suitability; however, refined rice- and maize-based gluten-free products may be limited in protein quality, dietary fiber, minerals, and bioactive compounds. In this context, millets and pseudocereals are gaining attention among both gluten-sensitive and health-conscious consumers because they are naturally gluten-free and nutritionally dense. Millets provide complex carbohydrates, dietary fiber, proteins, minerals, vitamins, antioxidants, and bioactive compounds, while pseudocereals generally offer high-quality proteins, balanced essential amino acids, beneficial lipid fractions, minerals, and phytochemicals.[46–48] Thus, these grains represent valuable alternatives for developing gluten-free products with improved nutritional quality, functional value, and dietary diversity. A comparative overview of conventional cereal staples and millets/pseudocereals in relation to gluten-free food development is presented in Table 3.

Millets are traditional staple crops grown in arid and semi-arid regions, belonging to the "*Chlorideae*" and "*Paniceae*" tribes within the *Poaceae* family. They are cultivated in dry areas of Asia, India, China, and Africa and were commonly consumed before the rise of modern cereals like wheat and rice.[49] In April 2018, millets were officially recognized as "nutri-cereals" in India, which also celebrated "The Year of Millets" to enhance the production of these nutrient-rich grains. Additionally, the FAO also declared 2023 as the "International Year of Millets".[50]

On the basis of grain size millets can be classified into major millets and minor millets. Major millets comprise pearl millet (*Pennisetum glaucam*), sorghum (*Sorghum vulgare*), and finger millet (*Eleusine coracana*) whereas minor millets include foxtail millet (*Setaria italica*), browntop millet (*Urochloa ramosa*), proso millet (*Panicum miliaceum*), kodo millet (*Paspalum setaceum*), little millet (*Panicum sumantrense*), and barnyard millet (*Echinochloa utilis*).[51] Millets, often termed "smart crops", are advantageous for human health, environmental sustainability, and agricultural resilience. They produce less elastic and cohesive dough compared to wheat due to their non-glutinous nature.[52] However, millets offer a superior nutritional profile, containing approximately 60–70% carbohydrates, 1.5–5% fat, 6–19% protein, 12–20% total dietary fiber, and 2–4% minerals, although these values vary with species, cultivar, growing conditions, and processing level. They are rich in B vitamins, minerals, antioxidants, and dietary fiber, though low in lysine and threonine. Millets are used in diverse foods, including chapatti, bread, and as sources of prebiotics and probiotics.[53]

Pseudocereals are edible seeds from dicotyledonous species that resemble true cereals in physical appearance and high starch content, despite their classification in different botanical families.[7] These crops are gaining attention as future staples

Table 3 Comparative overview of conventional cereal staples and millets/pseudocereals for gluten-free food development

Parameter	Conventional cereal staples: wheat, rice, and maize	Millets and pseudocereals	Implication for gluten-free food development	References
Gluten status and dietary use	Wheat contains gluten and is unsuitable for individuals with gluten-related disorders. Rice and maize are naturally gluten-free but are commonly used in refined starch-based gluten-free products	Millets and pseudocereals are naturally gluten-free and can diversify gluten-free formulations beyond rice- and maize-based ingredients	Diversifies gluten-free product development beyond rice- and maize-based staples	Martínez-Villaluenga *et al.*;[7] Selladurai *et al.*[8]
Protein and amino acid composition	Rice and maize proteins are generally limited in lysine, and refinement may further reduce their nutritional quality. In contrast, wheat contains higher protein levels but is unsuitable for gluten-free diets due to gluten-forming proteins	Millets provide moderate protein levels, while pseudocereals such as quinoa, amaranth, and buckwheat show better amino acid balance and higher protein quality	Enhances the protein content and nutritional quality of gluten-free formulations	Martínez-Villaluenga *et al.*;[7] Nandan *et al.*[47]
Dietary fiber and starch digestibility	Whole rice and maize contain dietary fiber, but polishing/refining reduces fiber-rich fractions. Many rice- and maize-based gluten-free products are starch-rich and may show rapid starch digestibility	Millets and pseudocereals contain dietary fiber, resistant starch, and slowly digestible carbohydrate fractions, depending on species and processing level	Supports improved fiber content, satiety, gut-health relevance, and glycemic response	Allouch Tounsi *et al.*;[45] Khan *et al.*[48]
Mineral and vitamin content	Polished rice and refined maize may lose minerals and vitamins during removal of bran and germ layers. Wheat contains micronutrients but is not suitable for gluten-free diets	Millets and pseudocereals provide minerals such as calcium, iron, magnesium, phosphorus, and zinc; finger millet is especially notable for calcium, while quinoa, amaranth, and buckwheat contribute diverse minerals and vitamins	Can improve micronutrient contribution in gluten-free formulations, especially when minimally processed flours are used	Nandan *et al.*[47]
Product formulation	Rice and maize are widely used in gluten-free products due to their availability, established processing suitability, and compatibility with different product formats; however, refined rice- or maize-based formulations often require blending, fortification, hydrocolloids, or protein/fiber enrichment to improve nutritional and textural quality	Millets and pseudocereals can be incorporated into bakery products, pasta, noodles, snacks, beverages, and infant foods, either alone or in blends, to improve nutritional quality and product diversity	Supports the development of nutritionally improved, diversified, and functionally enhanced gluten-free products	Martínez-Villaluenga *et al.*;[7] Selladurai *et al.*;[8] Towa *et al.*[118]

due to their genetic diversity, which enhances their adaptability to a range of environmental conditions, from tropical to temperate climates.[54] Key pseudocereal species include quinoa (*Chenopodium quinoa* Willd.), amaranth (*Amaranthus* sp.), and buckwheat (*Fagopyrum* sp.). Quinoa and amaranth belong to the *Chenopodiaceae* family and originated in the Andean region of South America. Buckwheat, which is classified under the *Polygonaceae* family, encompasses three cultivated species: *F. sculentum* (common buckwheat), *F. tataricum* (tartary buckwheat), and *F. cymosum* (tall buckwheat), all native to Central and Western China.[47] Pseudocereals generally have higher protein and lipid levels and lower carbohydrates compared to traditional grains like maize, wheat, and rice. They are rich in bioactive compounds such as dietary fiber, unsaturated fatty acids, lignans, antioxidants, flavonoids, polyphenols, phytosterols, minerals, and vitamins, and offer high-quality proteins with balanced amino acid profiles and superior digestibility.[55] Pseudocereals are associated with various health benefits, including hypolipidemic, anti-inflammatory, anti-hypertensive, anti-cancer, hepatoprotective effects, and support for obesity and diabetes management.[7,56]

Consumers place a high value on nutritional quality to support health and well-being. Millets and pseudocereals, as gluten-free (GF) grains, are gaining popularity due to their superior nutritional profiles and health benefits. Recent research highlights their value as functional foods and their potential in gluten-free product development.[54]

5.1 Sustainability indicators of millets and pseudocereals

Millets provide measurable environmental advantages over several conventional cereal crops, particularly in terms of carbon footprint and climate resilience. Pearl millet and sorghum have been reported to exhibit lower carbon footprints of 3218 and 3358 kg CO_2-eq per ha, respectively, compared with major cereals, which generally range from 3700 to 9900 kg CO_2-eq per ha. Sharma *et al.*[57] also reported higher values for maize, wheat, and rice, with carbon footprints of 4052, 5455, and 11 881 kg CO_2-eq per ha, respectively. This lower emission burden is mainly attributed to the reduced requirement for synthetic fertilizers, pesticides, irrigation, and fossil-fuel-intensive field operations, along with their tolerance to drought and heat stress. In addition to lower emissions, millets also show higher carbon sequestration potential, ranging from 499.6 to 4024.7 C mg per ha per year, compared with cereal crops, pulses, and oilseed crops. These indicators strengthen the role of millets as low-carbon, climate-resilient crops suitable for sustainable gluten-free food systems.[57] Among pseudocereals, quinoa has also shown measurable sustainability potential, with a reported carbon footprint of 1159.65 kg CO_2-eq per ha, indicating its relevance as a resource-efficient gluten-free grain.[58]

6 Nutritional composition of millets and pseudocereals

Millets and pseudocereals are nutritionally valuable gluten-free grains that can improve the quality of gluten-free diets beyond refined starch-based formulations. Millets, despite species-specific differences in grain size, structure, and composition, generally contain 60–75% carbohydrates, mainly as starch, 12–20% total dietary fiber, 8–15% protein, 1–5% lipids, and 1–3% ash, although these values vary with species, cultivar, growing conditions, and processing level.[59] Compared with conventional refined gluten-free ingredients, millets provide complex carbohydrates, dietary fiber, minerals, and bioactive compounds that can contribute to improved nutritional quality. Pseudocereals such as quinoa, amaranth, buckwheat, and chia also show a strong nutritional profile, often characterized by higher-quality proteins, beneficial lipid fractions, minerals, dietary fiber, and diverse bioactive compounds, including phenolic acids, flavonoids, and phytosterols.[14,47,55]

Among pseudocereals, quinoa is considered a balanced source of carbohydrates, proteins, lipids, and minerals, and its starch exhibits good stability, particularly in food systems requiring viscosity retention during freezing and thawing.[60] Buckwheat, especially tartary buckwheat, is notable for its high flavonoid content, particularly rutin and related phenolics, which contribute to its antioxidant potential as well as characteristic bitterness. Amaranth, which includes more than 400 species, is a valuable source of protein, dietary fiber, minerals, and unsaturated fatty acids, particularly ω-6 fatty acids, and has been associated with cholesterol management and type-2 diabetes control.[61] Chia seeds are distinguished by their high lipid content, approximately 30–38%, predominantly ω-3 fatty acids, along with dietary fiber, minerals, and antioxidants, making them useful not only nutritionally but also technologically as emulsifying and stabilizing ingredients in food applications.[62] The comprehensive nutritional composition of millets and pseudocereals is summarized in Table 4.

The nutritional profile of millets and pseudocereals is particularly relevant for individuals with gluten-related disorders, especially coeliac disease, where nutrient malabsorption and long-term gluten-free dietary restrictions may increase the risk of iron deficiency anemia, inadequate calcium and vitamin D intake, reduced bone mineral density, osteopenia, osteoporosis, and low dietary fiber intake.[63,64] Finger millet is especially important in this context because it is one of the richest cereal sources of calcium, commonly reported at approximately 344 mg/100 g, and can improve the mineral quality of gluten-free formulations targeted toward bone-health support.[8,65] Similarly, pseudocereals such as quinoa, amaranth, and buckwheat contribute protein, iron, magnesium, calcium, dietary fiber, and bioactive compounds, thereby helping address nutritional gaps commonly observed in gluten-free diets.[47,66]

The health-promoting effects of millets and pseudocereals are largely associated with their diverse bioactive compounds, including phenolic acids, flavonoids, phytosterols, lignans, and antioxidant peptides. Phenolic compounds in finger millet, buckwheat, quinoa, and amaranth have been linked with antioxidant and anti-inflammatory activity by reducing oxidative stress and modulating inflammatory pathways. In addition, dietary fiber, unsaturated fatty acids, phytosterols, and polyphenols may contribute to cardioprotective effects through cholesterol reduction, improved lipid metabolism, glycemic

Table 4 Comprehensive nutritional profile of millets and pseudocereals: protein fractions amino acid, fatty acid, macrominerals, and vitamin composition[a]

Nutritional components	Pearl millet	Proso millet	Finger millet	Foxtail millet	Kodo millet	Barnyard millet	Amaranth	Buckwheat	Quinoa
Energy (kcal)	363	341	320	331	353	307	371	343	368
Moisture (%)	8.9	11.9	10.8	11.2	14.2	11.9	8.9–9.4	11.0	8.2–13.1
Ash (g)	2.2	3.1	2.6	3.3	3.3	4.5	6.7	2.1	2.4
Carbohydrate (g)	61.7	70.0	66.8	60.0	66.1	65.5	63.1–70.0	63.1–82.1	48.5–77
Protein content (% dry weight)	10.9	12.5	7.1	12.3	8.9	6.2	13.6	13.3	14.1
Total fat (%)	5.4	1.1	1.9	4.30	2.5	2.2	7.0	3.4	6.1
Protein fractions (% of total protein)									
Albumin	22–28	8.6–9.5	13.3	13	—	11.3–17.2	11–52	26.96	35
Globulins	22–28	4.1–6.1	14.0	13	—	11.3–17.2	16–52	41.3	37
Prolamins	22–35	47.2–50.8	22.1	39.4	—	14.3–20.9	2–13	1.7	0.5–7.0
Glutelins	28–32	34.5–39.1	10.6	9.9	—	45.2–63.5	7–36	23.16	5–36
Amino acid content (essential amino acids) (g/100 g)									
Histidine	1.7	2.1	2.3	2.14	2.23	2.42	1.9–3.8	1.8–4.9	1.4–5.4
Isoleucine	5.1	4.1	4.3	4.55	4.44	6.04	2.7–4.2	1.1–4.1	0.8–7.4
Leucine	14.1	12.2	10.8	11.96	10.84	12.46	4.2–6.9	2.2–7.6	2.3–9.4
Lysine	0.5	1.5	2.2	1.42	1.91	2.13	4.8–8.0	4.2–8.6	2.4–7.8
Methionine	1.0	2.2	2.9	2.69	2.73	3.08	1.6–4.6	0.5–2.5	0.3–9.1
Phenylalanine	7.6	5.5	6.0	6.27	9.56	6.86	3.7–4.7	1.3–7.2	3.0–4.7
Threonine	3.3	3.0	4.3	3.89	3.85	4.72	3.3–5.0	3.9–4.0	2.1–8.9
Tryptophan	1.2	0.8	NA	1.32	1.32	1.31	0.9–1.8	1.83	0.6–1.9
Valine	4.2	5.4	6.3	5.49	6.78	6.59	3.9–5.0	2.3–6.1	0.8–6.1
Essential fatty acid (%)									
Alpha-linolenic acid C18:3 ω-3	2.15	1.61	1.6	2.48	—	1.5–1.7	0.6–1.4	0.0–5.3	3.0–11.1
Linoleic acid (%) C18:2 ω-6 cis	47.50	61.74	19.0	66.68	—	46.4–48.1	37.1–45.9	31.4–44.6	44.9–58.6
Total dietary fiber (g)	11.4	14.2	18.8	14	15	13.7	2.7–17.3	17.8	7.0–26.5
Soluble dietary fiber (% total fiber)	2.6	2.4	3.7	2.7	2.2	2.0	14.0–22.0	16.0	22.0
Insoluble dietary fiber (% total fiber)	11.5	16.1	20.4	23.0	31.7	26.1	78.0–86.0	70.3	78.0
Macro-minerals (mg/100 g)									
Calcium (Ca)	42	14	344	32.33	35	17.1–32.7	159	18	47
Phosphorus (P)	307	206	283	270–310	300	281	557	347	457
Magnesium (Mg)	137	153	137	101.1	110	18.6	248	231	197
Potassium (K)	296	206	283	250–400	141	298	508	460	563
Vitamins									
Thiamin (Vit-B1)	0.25	0.41	0.37	0.59	0.29	0.33	0.12	0.10	0.36
Riboflavin (Vit-B2)	0.20	0.28	0.17	0.11	0.20	0.10	0.20	0.43	0.32
Niacin (Vit-B3)	0.86	4.50	1.34	3.20	1.49	4.2	0.92	7.02	1.52

[a] Source: Gowda *et al.*;[69] Nandan *et al.*;[47] Saleem *et al.*;[71] Martínez-Villaluenga *et al.*;[7] Schmidt *et al.*;[74] Bhatt *et al.*;[119] Akharume *et al.*;[72] Krishnan and Meera.;[76] Vinoth and Ravindhran.;[120] Janssen *et al.*;[121] Hassan *et al.*;[73] Sachdev *et al.*;[51] Slama *et al.*;[122] Shen *et al.*;[123] Zhang *et al.*;[124] Yousaf *et al.*;[88] Yang *et al.*;[125] Longvah *et al.*[126]

regulation, and protection against oxidative damage.[7,47,67,68] The minimal prolamin content in pseudocereals also makes them suitable for individuals with celiac disease, enhancing their dietary fiber benefits.[66]

6.1 Carbohydrate profile

Millets provide energy in the range of 320–370 kcal per 100 grams of consumption (Table 4) and consist of 65–75% carbohydrates, with a higher proportion of non-starchy polysaccharides and dietary fiber than staple cereals.[69] Millets are composed of approximately 70% carbohydrates, mainly starch, with an amylopectin-to-amylose ratio of 3 : 1 to 4 : 1, and a significant amount of dietary fiber. Their slow-digesting complex carbohydrates help regulate blood sugar levels, making them suitable for managing diabetes and obesity.[59,70]

Pseudocereals like quinoa, amaranth, and buckwheat have carbohydrate contents of 50–80%, with smaller starch granules that enhance the texture of flours. Quinoa's starch content ranges from 52% to 60%, with a low amylose content (11%). Buckwheat contains 58–73% starch, with amylose comprising 18.3–47% of the total starch, and resistant starch levels as high as 35%.[67] Amaranth has a starch content of 65–75%, with amylose ranging from 7.8%–34.3%. These grains are also rich in dietary fiber, exhibiting slower digestion due to the high cell wall matrix in their endosperm, making them ideal for managing blood glucose and digestive health.[47] Both millets and pseudocereals, through their high fiber and resistant starch content, offer potential health benefits, including improved glycemic control and gut health, making them valuable for dietary management of diabetes and obesity.[7]

6.2 Protein and amino acid composition

The protein content of millets typically ranges from 6% to 12%, depending on species, cultivar, and growing conditions.[71] Millet proteins are broadly classified into albumins, globulins, prolamins, and glutelins; however, the relative distribution of these fractions varies considerably among millet species. Prolamins and glutelins generally represent important storage protein fractions, while albumins and globulins also contribute to the overall protein profile. In proso millet, for instance, albumin, globulin, prolamin, and glutelin have been reported to account for 9.5%, 4.1%, 47.2%, and 39.1% of total protein, respectively.[72] In contrast, pearl millet shows a comparatively lower prolamin proportion of approximately 22–35%, indicating species-dependent variation in protein fraction distribution.[59,73] Millet proteins, including essential amino acids, complement legumes and animal proteins, offering balanced nutrition. Finger millet and quinoa are notable for their high sulfur-containing amino acids and protein content similar to milk, while foxtail millet is distinguished by its high lysine levels. Additionally, millet proteins are hypoallergenic and suitable for children and the elderly.[70] Foxtail millet is considered superior due to its higher content of amino acids like lysine, threonine, and valine. Compared to sorghum and corn, pearl millet has more lysine, threonine, and methionine, along with higher digestibility values. Its amino acid profile is also comparable to wheat, barley, and rice.[73] Millet prolamins, which are low in lysine, dominate in major species like pearl (43% of total protein), finger, foxtail, and proso millet.[59]

Pseudocereals such as quinoa, amaranth, and buckwheat have higher protein content ranges from 13–14% with superior protein quality compared to millets, and are rich in essential amino acids like lysine, threonine, and methionine. These pseudocereal proteins primarily consist of globulins and albumins, which are gluten-free and hypoallergenic, unlike the prolamins found in most cereals.[74] Pseudocereals, including quinoa, are distinguished by their balanced amino acid profiles with higher levels of lysine, methionine, and cysteine compared to common cereals, which typically lack lysine and, to a lesser extent, threonine and tryptophan. In quinoa, the main protein fractions are 11S-type globulins and 2S albumins, which make up 27.9–60.2% and 13.2–42.3% of the total protein, respectively, while glutelins account for 18.1–31.6%. Prolamins are present in smaller quantities, ranging from 0.5–19.3%.[7]

Both millets and pseudocereals provide valuable gluten-free protein sources. While millets offer essential amino acids, pseudocereals deliver higher protein quality, making them superior for enhancing dietary protein intake, especially in gluten-free diets.[47]

6.3 Lipid content and fatty acid profile

Millets have a lipid content ranging from 1.1 to 5.4 g/100 g.[71] They are notably high in unsaturated fatty acids, which offer cardiovascular benefits. Among the different millet varieties, pearl millet has the highest free lipid content at 56.7 mg g^{-1}, followed by little millet at 49.7 mg g^{-1}, foxtail millet at 46.8 mg g^{-1}, and finger millet at 9.3 mg g^{-1}.[75] Pearl millet and foxtail millet exhibit higher lipid contents due to their large germ portions, with the germ of pearl millet accounting for 32% of its total fat. In contrast, finger millet has a lower fat content (around 1.4%) and is dominated by monounsaturated oleic acid, which contributes to its long shelf life.[59] Foxtail millet bran oil is particularly beneficial due to its high levels of polyunsaturated fatty acids (PUFAs) like linoleic and linolenic acids, and monounsaturated fatty acids (MUFAs) such as oleic acid, which help reduce LDL cholesterol and increase HDL cholesterol.[71]

Pseudocereals such as quinoa, amaranth, and buckwheat are notable for their higher fat content, ranging from 3–7%. In quinoa and amaranth, linoleic acid (C18:2, ω-6) and α-linolenic acid (C18:3, ω-3) are the primary unsaturated fatty acids, while buckwheat oil is rich in oleic acid (C18:1) and linoleic acid. Quinoa's fat content includes high levels of linoleic (44.9–58.6%) and linolenic (3.0–11.1%) acids, making its fatty acid composition similar to soybean oil. Amaranth lipid composition includes 37.1–45.9% linoleic acid, 0.6–1.4% linolenic acid. Buckwheat, with a lower fat content is also rich in unsaturated fatty acids, including 31.4–44.6% linoleic acid, and 0.0–5.3 linolenic acid.[7,47,67] Pseudocereals, rich in unsaturated fatty acids like linoleic and α-linolenic acids, offer health benefits such as lower cardiovascular disease risk and reduced inflammation. Quinoa, in particular, has the highest α-linolenic acid concentration (4%) among pseudocereals and an omega-6 to omega-3 ratio of about 6 : 1, which enhances its nutritional value.[47] Chia seeds, among pseudocereals, stand out with a fat content of 30%, making them comparable to oilseeds. They are rich in omega-3 and omega-6 fatty acids, beneficial for cardiovascular and inflammatory health.[70]

6.4 Macronutrients and vitamins

Millet varieties demonstrate diverse mineral compositions, as outlined in Table 4, and are particularly rich in key minerals like calcium, phosphorus, magnesium, manganese, zinc, iron, and copper. However, the presence of compounds such as phytates, oxalates, and polyphenols in pearl millet may reduce the bioavailability of its iron content.[73] Finger millet is particularly rich in calcium content (344 mg/100 g). Additionally, finger millet provides significant amounts of magnesium, which is beneficial for disease prevention, including cancer.[71] The high calcium content in finger millet contributes to bone health by strengthening bones and reducing fracture risk.

Millets, while generally lower in provitamin A, are excellent sources of B vitamins, especially thiamine, riboflavin, and niacin. However, their vitamin E content is typically lower than that of pseudocereals and other cereals. Despite this, millets contribute to a nutrient-rich diet, with biofortified sorghum and pearl millet offering enhanced iron and zinc levels, exceeding 75 mg/100 g and 55 mg/100 g, respectively.[59] Pearl millet is a notable source of β-carotene, a precursor of vitamin A,[76] while the aleurone layer and germ of pearl millet contain high concentrations of B vitamins.[69]

Pseudocereal grains, with their minerals largely concentrated in the bran, are valuable mineral sources. Among them, amaranth has the highest mineral content, followed by quinoa and buckwheat, with tartary buckwheat exhibiting higher mineral levels than common buckwheat. Key minerals include potassium, phosphorus, and magnesium. The high calcium content in amaranth is particularly advantageous for individuals with celiac disease, who are at increased risk for bone-related conditions such as osteopenia and osteoporosis.[7]

Pseudocereals like amaranth, quinoa, and buckwheat are rich in vitamins and minerals, often surpassing conventional cereal grains. Amaranth is also notable for its vitamins, including vitamin C (4.5 mg/100 g), vitamin B2 (0.19–0.23 mg/100 g), and B3 (1.17–1.45 mg/100 g), as well as tocopherols and tocotrienols, ranging from 1.4 to 43.83 mg kg^{-1} for α-tocopherol and α-tocotrienol.[47] Quinoa is a good source of vitamin E, riboflavin, and vitamin B6, with concentrations of vitamin B1 (0.41 mg), B9 (78.1 mg), and vitamin E components including γ-tocopherol (47–53 μg g^{-1}) and α-tocopherol (17–26 μg g^{-1}). Quinoa is also rich in calcium, magnesium, and potassium, making it a nutritionally dense grain.[77] Buckwheat is similarly nutrient-rich, with higher concentrations of vitamins B1, B3, B6, γ-tocopherol (117.80 μg g^{-1}), and δ-tocopherol (7.30 μg g^{-1}). Its mineral content includes potassium, phosphorus, calcium (70.14 mg/100 g), and iron (3.4–6 mg/100 g) in common buckwheat, and up to 21.5 mg/100 g iron in tartary buckwheat.[78]

Overall, both millets and pseudocereals contribute to better health through their rich mineral profiles and antioxidant properties, with notable benefits in managing blood sugar, cholesterol, and cardiovascular health.[59]

6.5 Dietary fiber and phytochemicals

Millets are rich in dietary fiber, generally containing approximately 12–20% total dietary fiber, with variation among species, cultivars, and processing conditions. The fiber fraction is predominantly insoluble, although soluble fiber is also present and contributes to glycemic regulation, cholesterol reduction, and digestive health. Dietary fiber values vary among millet species, cultivars, growing conditions, processing levels, and analytical methods. Values presented in the Table 4 represent reported ranges for specific grains. Moreover, millets contain antioxidants and phenolic compounds that help protect against aging and metabolic disorders.[59,70] Millets have a total dietary fiber content comparable to or greater than that of other cereals, ranging from 13 to 19 g. They contain insoluble dietary fiber (IDF) between 11.5% and 31.7%, and soluble dietary fiber (SDF) between 2.0% and 3.7%. IDF in millets surpasses that in wheat, maize, and barley, while SDF levels are slightly lower than those in wheat. Kodo millet has the highest IDF content, whereas finger millet is noted for its high SDF.[69,75]

Pseudocereals such as quinoa, amaranth, and buckwheat are also excellent sources of dietary fiber, primarily consisting of polysaccharides and lignin, which are fermented in the large intestine. Quinoa has a total dietary fiber content of 7.0% to 26.5%, with 78% being insoluble fiber, such as cellulose and xyloglucans, and 22% soluble fiber, including xyloglucans and pectic polysaccharides. Buckwheat contains 17–26% fiber, with dehulled seeds comprising 2.90% insoluble and 2.40% soluble fiber, largely consisting of pectin, arabinogalactans, and hemicellulose. Amaranth's fiber ranges from 2.0% to 20.6%, with the insoluble fraction mainly composed of arabinose and galacturonic acid.[7,67] These fibers improve digestion, reduce cholesterol, regulate blood sugar, and offer protection against heart disease and diabetes.[79]

7 Anti-nutrient challenges in millets and pseudocereals: strategies for enhancing food value

Antinutrients are naturally occurring plant constituents that can reduce nutrient utilization by interfering with mineral absorption, protein and starch digestibility, and digestive enzyme activity. The major antinutritional factors reported in millets and pseudocereals include phytates, tannins, oxalates, saponins, and enzyme inhibitors such as trypsin and chymotrypsin inhibitors. Compared with commonly consumed cereals such as wheat and rice, millets and pseudocereals may contain relatively higher levels of some antinutritional compounds, although their concentration varies widely with species, cultivar, growing conditions, grain fraction, and processing method.[69,80] For example, phytic acid in pearl millet has been reported in the range of 477–920 mg/100 g, which may reduce phosphorus and mineral availability by forming insoluble complexes.[73]

Antinutritional factors affect nutrient bioavailability through different mechanisms. Phytates chelate essential minerals such as iron, zinc, calcium, and magnesium, thereby reducing their bioavailability and potentially impairing protein digestion. Tannins form complexes with proteins and digestive enzymes, which can reduce amino acid availability and protein digestibility. Oxalates can bind calcium and lower its availability, while saponins may interact with cholesterol and membrane components and influence digestive processes. Similarly, protease inhibitors can reduce the activity of digestive enzymes such as trypsin and chymotrypsin, thereby affecting protein digestion and nutrient absorption.[80] Various processing methods, including soaking, germination, fermentation, roasting, puffing, popping, milling, and extrusion, are therefore applied to reduce antinutrient levels in millets and pseudocereals, as summarized in Table 5.

The improvement in bioavailability and sensory quality during processing is driven by biochemical, microbial, and structural changes in the grain matrix. Germination activates

Table 5 Effect of processing on millets and pseudocereals

Processing method	Effects on antinutrients	Advantages	Limitations	References
Dehulling/decortication	Removes antinutrient-rich husk, bran, and seed coat; reduces phytates, tannins, oxalates, and phenolics. In browntop millet, tannins and phytates decreased by 59.4% and 22.1%, respectively	Improves colour, palatability, cooking quality, acceptability, and processing suitability	May reduce fiber, minerals, vitamins, and bioactive compounds; generates bran/husk by-products	Thakur *et al.*;[14] Stanley *et al.*[89]
Soaking	Soaking reduces soluble antinutrients through leaching, hydration-induced structural loosening, and partial phytase activation. In pearl millet, conventional soaking for 12–24 h reduced phytic acid and tannins by up to 87.77% and 89.17%, respectively, while high-pressure soaking reduced phytate by up to 80.61% and increased free iron availability	Improves hydration, cooking quality, mineral availability, and digestibility; supports germination/fermentation	Requires water and generates wastewater; efficiency depends on grain type and soaking conditions	Himashree and Mahendran.;[91] Hemanth *et al.*;[90] Samtiya *et al.*;[80] Nandan *et al.*[47]
Germination/malting	Activates phytase, amylase, protease, lipase, and cell-wall-degrading enzymes; reduces phytates, tannins, saponins, oxalates, and enzyme inhibitors. Major antinutrients may decline by 55–65%, with tannin reduction up to 83% under alkali-assisted germination	Enhances vitamins, minerals, antioxidant activity, phenolics, amino acids, sugars, protein digestibility, bioactive peptides, and mineral bioaccessibility	Requires controlled moisture, temperature, hygiene, and drying; improper conditions may cause microbial spoilage	Agregán *et al.*;[92] Dey *et al.*;[93] Thakur *et al.*;[86] Chauhan.;[95] Bhavadharani *et al.*;[94] Altıkardeş *et al.*;[97] Karki *et al.*;[96] Mundassery *et al.*[98]
Fermentation	Degrades phytic acid, tannins, tannin–protein complexes, and enzyme inhibitors through microbial acidification, phytase activity, and hydrolysis. Phytic acid reduction ranges from 20.96–54.53%	Improves mineral bioavailability, protein/starch digestibility, flavour, acceptability, shelf-life, B-vitamins, antioxidants, and bioactive peptides	Requires controlled cultures, hygiene, time, and standardization; uncontrolled fermentation causes quality variation	Sheethal *et al.*;[99] Sadh *et al.*;[81] Kitessa *et al.*;[82] Tomar *et al.*[83]
Milling/fractionation	Reduces particle size and removes bran-associated phytates, tannins, phenolics, and other outer-layer antinutrients	Improves flour functionality, hydration, uniformity, cooking quality, and product diversification	May reduce fiber, minerals, vitamins, lipids, and bioactives; by-products require utilization	Dey *et al.*;[93] Mundassery *et al.*;[98] Stanley *et al.*[89]
Roasting	Reduces moisture, microbial load, enzyme inhibitors, and some heat-labile antinutrients	Improves flavour, aroma, colour, crispness, digestibility, and shelf stability	Excessive heating may reduce heat-sensitive nutrients and increase acrylamide risk	Gowda *et al.*;[69] EFSA CONTAM Panel.;[100] Mesías *et al.*[101]
Puffing/popping	High-temperature short-time processing disrupts grain structure and reduces antinutrients. In finger millet, phytic acid decreased from 851.4 to 333.1 mg/100 g and tannins from 870.8 to 610.2 mg/100 g	Improves digestibility, texture, crispness, flavour, convenience, starch accessibility, and cooking time	Requires energy and process control; excessive heat may reduce nutrients and increase contaminant risk	Chauhan.;[95] EFSA CONTAM Panel.;[100] Mesías *et al.*[101]
Extrusion	Heat, shear, pressure, and mechanical energy reduce some antinutrients and restructure starch–protein matrices	Improves expansion, texture, water absorption, digestibility, uniformity, and convenience; suitable for RTE foods	Requires equipment, energy, and optimization; excessive processing may reduce nutrient retention	Anal.;[84] Reddy *et al.*[85]

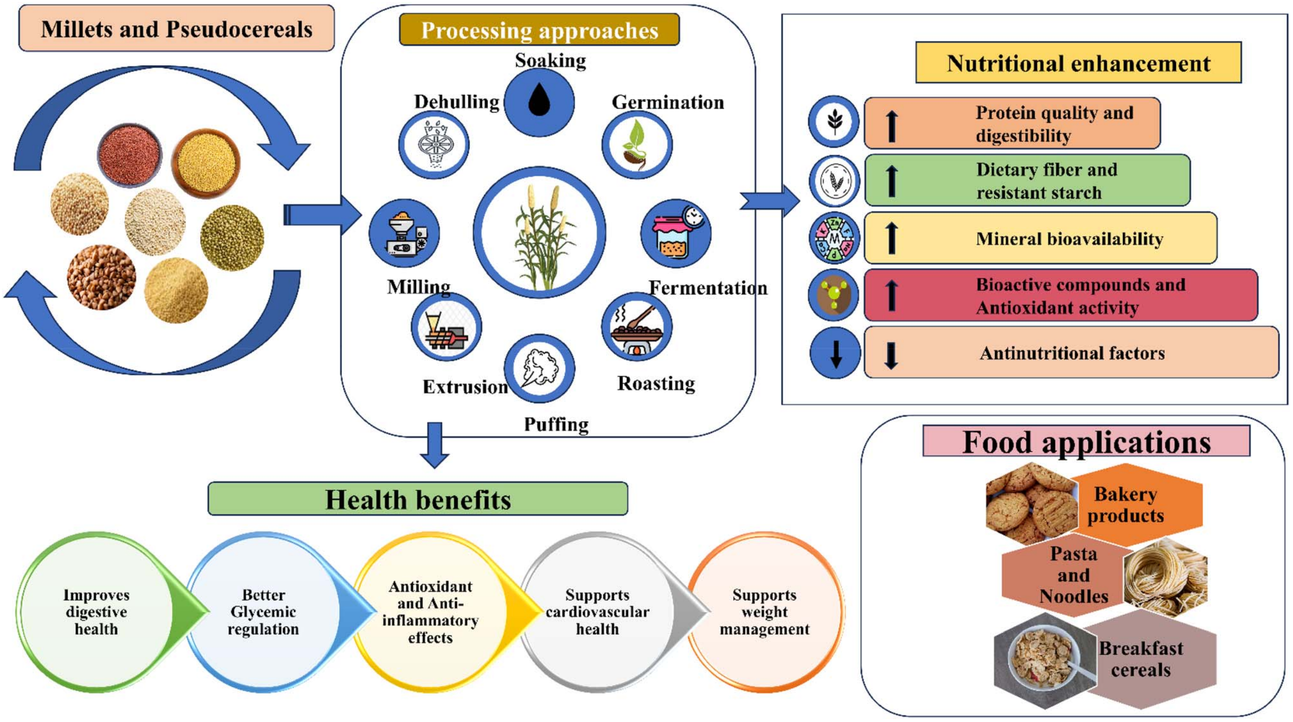


Fig. 5 Impact of processing on nutritional and health attributes of millets and pseudocereals.

endogenous enzymes such as phytase, amylase, and protease, which degrade phytate–mineral complexes and improve starch and protein digestibility. Fermentation enhances nutrient availability through microbial acidification, enzymatic hydrolysis, phytic acid degradation, and formation of flavour-active metabolites such as organic acids, alcohols, and esters, thereby improving taste, aroma, and acceptability.[81–83] Extrusion and other high-temperature treatments modify starch and protein structures through heat, shear, and pressure, leading to starch gelatinization, protein denaturation, improved water absorption, and better textural characteristics in gluten-free products.[84,85] Thus, processing should be optimized to balance antinutrient reduction, nutrient retention, sensory improvement, and product functionality. The relationship between processing techniques, nutritional enhancement, and associated health benefits of millets and pseudocereals is summarized in Fig. 5.

7.1 Dehulling

Dehulling, or the removal of the outer layer and pericarp of grains, is a critical step in the processing of millets and pseudocereals but can result in the loss of key nutrients. This process removes approximately 12–30% of the grain kernel, leading to significant reductions in dietary fiber, bioactive compounds, and up to 80% of phenolic content, which is predominantly concentrated in the husk and seed coat.[47] Dehulling or decortication reduces antinutrient levels primarily by removing the bran, husk, and outer seed coat, where phytates, tannins, and other antinutritional compounds are largely concentrated. In addition to improving palatability, grain colour, and overall processing quality, dehulling can enhance nutritional accessibility by lowering phytic acid and tannin contents.[14] For example, in browntop millet, dehulling reduced tannin content from 0.64 to 0.26 mg g^{-1} and phytate content from 1.04 to 0.81 mg g^{-1}, corresponding to reductions of approximately 59.4% and 22.1%, respectively.[87] Comparative studies of traditional and modern decortication techniques in pearl millet have demonstrated reductions in macronutrient contents, including protein, crude fiber, oil, and ash, alongside substantial decreases in antinutrient levels, particularly tannins, phytic acid, and essential minerals such as calcium, iron, and phosphorus. While dehulling effectively reduces antinutrients and improves nutrient bioavailability, it also results in considerable nutrient losses, particularly from the outer layers of the grain.[88] From a sustainability perspective, dehulling is a simple mechanical process, but it generates bran, husk, and germ by-products; these fractions can be valorized as fiber-rich ingredients, animal feed, or sources of phenolics, flavonoids, tannins, and lignans, thereby reducing processing waste and improving resource efficiency.[89]

7.2 Soaking

Soaking is a simple hydration-based preprocessing technique that improves grain hydration and facilitates the removal of water-soluble or diffusible antinutritional compounds. During soaking, water diffusion into the grain matrix can promote leaching of soluble antinutrients and partial activation of endogenous enzymes such as phytase, thereby reducing phytic acid and improving mineral bioavailability.[47,80] This process also supports subsequent treatments such as germination and fermentation, which can further enhance antinutrient degradation and nutrient accessibility.[88] The reduction in phytic acid during soaking has been reported in millets and pseudocereals. Recent evidence shows that soaking is an effective pretreatment for reducing antinutrients in millets. Hemanth *et al.*[90] evaluated 30 pearl millet genotypes and reported that soaking for 12–24 h significantly reduced phytic acid and tannins, with the highest reductions reaching 87.77% for phytic acid and 89.17% for tannins. The authors suggested that 12 h soaking provided the best balance between antinutrient reduction and mineral retention. Another study reported High-pressure soaking of pearl millet reduced phytate content by up to 80.61% and increased free iron from 127.73 to 579.24 mg kg^{-1}, indicating improved mineral bioavailability.[91] Soaking may also reduce total polyphenolic content, possibly due to leaching and enzymatic oxidation through polyphenol oxidase activity, although the extent of reduction depends on grain type, soaking duration, temperature, and water-to-grain ratio.[80]

In addition to mineral bioavailability, soaking can improve protein and starch digestibility by reducing antinutrients that interfere with proteolytic and amylolytic enzymes. For example, protein digestibility has been reported to increase from 62.3% to 76% after soaking, reflecting the reduction of enzyme-inhibiting compounds and improved accessibility of grain proteins.[47] In pseudocereals, soaking and germination have shown marked reductions in antinutritional factors; Thakur *et al.*[86] reported reductions in tannin and phytic acid contents of 32.30% and 29.57% in amaranth, 59.91% and 17.42% in buckwheat, and 27.08% and 47.57% in quinoa, respectively. Although soaking is a low-energy and easily scalable pretreatment, its industrial sustainability depends on optimizing soaking time, minimizing water use, and ensuring proper wastewater management.

7.3 Germination

Germination, also referred to as sprouting or malting depending on the process conditions, involves controlled hydration followed by activation of grain metabolism. During this process, endogenous enzymes such as phytase, α-amylase, protease, and lipase become active and mobilize stored nutrients. Phytase hydrolyses phytic acid, thereby reducing phytate–mineral complexes and improving mineral bioavailability, while amylases and proteases partially degrade starch and storage proteins, improving starch and protein digestibility.[92,93] In pseudocereals such as quinoa, buckwheat, and amaranth, reductions in carbohydrates and lipids during germination have been attributed to metabolic utilization of reserves and increased lipolytic activity.[86] Germination has been shown to substantially reduce antinutritional factors in both millets and pseudocereals, although the extent of reduction depends on grain type, germination duration, temperature, and pretreatment conditions. In pearl and barnyard millet, germination reduced oxalic acid, phytic acid, and tannins by approximately 65%, 55%, and 65%, respectively.[94] In finger millet, germination reduced tannin from 870.8 to 360.5 mg/100 g, phytic acid from 851.4 to 238.5 mg/100 g, oxalic acid from 45.8 to 29.8 mg/100 g, and trypsin inhibitor activity from 4188 to 2001 U g^{-1}.[95] Similarly, germination of finger millet for 48 h at 28 ± 2 °C reduced tannin and phytic acid by 32.23% and 48.38%, respectively.[96] In pseudocereals, alkali-assisted germination reduced tannin content by up to 83% in buckwheat and 20% in quinoa, indicating that pretreatment conditions strongly influence antinutrient mitigation.[97] In addition to antinutrient reduction, germination can increase the relative availability of protein, dietary fiber, and minerals and improve both protein and starch digestibility through enzymatic modification and reduction of inhibitory compounds.[93] Comparative studies have also shown that germination may be more effective than some other treatments, such as soaking and fermentation, in reducing polyphenol content, depending on grain type and processing conditions.[88] From a sustainability perspective, germination is a low-chemical and nutritionally beneficial process; however, controlled moisture, hygienic handling, and adequate drying are required to prevent microbial spoilage and maintain shelf stability during industrial application.[98]

7.4 Fermentation

Fermentation is a microbial process mediated by lactic acid bacteria, yeasts, or mixed cultures. It improves nutrient availability through acidification, phytase activity, enzymatic hydrolysis, and degradation of phytate–mineral and tannin–protein complexes. Fermentation also improves sensory quality by producing organic acids, alcohols, esters, and other flavour-active compounds that enhance aroma, taste, and acceptability.[82,83] In traditionally processed millets, cooking reduced phytic acid by 16.14–49.18%, while subsequent fermentation with or without curd reduced phytic acid by 20.96–54.53%, depending on millet type and processing conditions.[99] These findings indicate that fermentation is effective for improving mineral bioavailability and reducing phytate-related limitations in millet-based foods. Fermentation is comparatively sustainable because it is a low-energy biological process and can be performed using traditional or starter-culture systems; however, industrial application requires controlled cultures, hygienic processing, and process standardization.

7.5 Milling

Milling is a traditional method used to grind grains, including millets and pseudocereals into flour and separate the bran layer. This process effectively reduces anti-nutrient levels, such as phytic acid, lectins, and tannins, which are concentrated in the bran.[80] This process, however, results in the removal of the bran, which contains essential nutrients such as vitamins B and E, and minerals like iron, zinc, and calcium, leading to significant nutrient losses. Milling also reduces levels of antinutrients, such as phytic acid and polyphenols, thereby improving nutrient bioavailability.[88] Consequently, milling enhances the digestibility of starch and protein. Despite its technological benefits, milling can substantially modify the chemical composition of millet grains by removing bran- and germ-rich fractions, leading to losses of dietary fiber, minerals, vitamins, and bioactive compounds.[93] Therefore, milling conditions should be optimized to balance flour functionality with nutrient retention, while bran and other milling by-products should be recovered for value-added applications to improve resource efficiency and reduce processing waste.[89,98]

7.6 Puffing/popping

Puffing is a high-temperature short-time (HTST) technique that enhances the nutritional and functional properties of grains, making them suitable for producing nutritious and affordable snack formulations and ready-to-eat products. It improves aroma, flavor, and digestibility while reducing anti-nutrients, thus offering significant benefits in food formulation and commercial applications.[47] Puffing significantly affects the nutritional profile of millets and pseudocereals, with increased iron content observed in popped millet, while calcium content decreases.[88] Puffed quinoa shows lower ash content, likely due to amino acid degradation during processing. Additionally, the popping process reduces anti-nutrients such as tannins, phytates, and trypsin inhibitors in cereals and pseudocereals, improving protein digestibility and nutrient bioavailability. For instance, puffed finger millet has reduced levels of oxalic acid and trypsin inhibitors, which enhances its nutritional value and digestibility.[92] Popping reduced tannin, phytic acid, oxalic acid, and trypsin inhibitor activity in finger millet from 870.8 to 610.2 mg/100 g, 851.4 to 333.1 mg/100 g, 45.8 to 32.2 mg/100 g, and 4188 to 3090 U g^{-1}, respectively. In pearl millet, popping also reduced phytic acid from 516.57 to 373.82 mg/100 g, indicating its effectiveness in lowering antinutritional factors through thermal disruption and partial inactivation of enzyme inhibitors.[95] Puffed amaranth shows increased carbohydrate content but reduced protein and lysine levels, while puffed sorghum has higher total amino acids despite a decrease in lysine.[92] However, high-temperature short-time processes such as puffing, popping, roasting, and extrusion improve digestibility, flavour, and antinutrient reduction, but may also promote acrylamide formation in carbohydrate-rich foods. Acrylamide is primarily formed *via* the Maillard reaction involving free asparagine and carbonyl compounds derived from reducing sugars during thermal processing, particularly under low-moisture conditions and temperatures above 120 °C (EFSA CONTAM Panel, 2015).[100] Therefore, millet- and pseudocereal-based roasted, puffed, extruded, and ready-to-eat gluten-free products should be processed under controlled time–temperature and moisture conditions. Strategies such as avoiding excessive browning, optimizing roasting/puffing parameters, and monitoring acrylamide levels can help balance nutritional improvement with product safety.[101,102]

8 Millets and pseudocereals based food products

Millets and pseudocereals are increasingly popular in the food industry for their versatility in gluten-free products, such as bread, pasta, biscuits, and confectionery. Although not true cereals, millets and pseudocereals can be processed into flour, serving as a nutritious alternative to conventional grains. Their increasing utilization is driven by the rising demand for gluten-free options, particularly among individuals with celiac disease.[79] Millets and pseudocereals, including amaranth, quinoa, and buckwheat, are distinguished by their gluten-free properties and are rich in protein, fiber, and bioactive compounds. This nutritional profile makes them valuable for enhancing the quality of gluten-free diets.[7] These grains offer a gluten-free replacement and contribute to the development of healthier and more nutrient-dense food products Table 6 highlights gluten-free products from millets and pseudocereals.

8.1 Gluten-free bakery products

Research on gluten-free bakery products has demonstrated the potential of millets and pseudocereals and other functional ingredients to improve both nutritional quality and sensory attributes. Sarabhai *et al.*[103] reported that enzyme-treated breads, particularly those treated with protease (PR), exhibited enhanced specific volume and crumb springiness, along with significantly reduced crumb hardness, chewiness, and cohesiveness compared to glucose oxidase and xylanase treatments. Protease-treated breads were also favored in sensory assessments for their superior physical and textural qualities, leading to higher acceptability.

Aguiar *et al.*[11] explored the impact of pseudocereal flours on gluten-free bread (GFB) quality, showing that buckwheat flour (BF) enhanced dough consistency, improving bread structure, volume, and texture. Single formulations using BF and QF result in moderate bread acceptability (scores of 6.7 and 6.4), whereas AF produces less acceptable bread (score of 5.4) due to its intrinsic odor and flavor, which also negatively affects texture. Blending these pseudocereal flours with rice flour (RF) significantly improved dough consistency, bread volume, softness, and overall acceptability. Optimal blends of 50% AF, BF, or QF with RF produced bread with high sensory scores, with maximum acceptable proportions of 60% AF, 85% BF, and 82% QF with RF.

In addition, malting of tartary buckwheat (*Fagopyrum tataricum* L. Gaertn.) significantly increased its phenolic profile and antioxidant activity. Gluten-free cookies made by substituting 30% rice flour with tartary buckwheat malt exhibited higher total phenolic content, particularly quercetin, and demonstrated increased antioxidant activity and a lower glycemic index compared to control cookies.[104] Similarly, the incorporation of carboxymethyl cellulose (CMC) into foxtail millet flour (FMF) improved the quality of biscuits, increasing thickness, specific volume, and moisture content.[105]

8.2 Gluten-free beverages

Research highlights the potential of millets and pseudocereals in gluten-free beer production. The production of gluten-free beer using unmalted millet and enzyme-assisted saccharification was investigated by Dymchenko *et al.*[106] Optimal enzymatic conditions (85 °C for amylosubtilin and 60 °C for glucavamarin and β-glucanase) successfully saccharified the wort. Roasted buckwheat (30%) was the best colorant, enhancing the overall appearance and taste. While all samples were gluten-free, the beverages resembled cider, lacking foam and having a low pH. Alcohol content was 2.8%. Further optimization of brewing and

Table 6 Gluten-free products from millets and pseudocereals

Products	Alternatives to wheat flour	Effects	Reference
Bread	Pearl millet-Bambara nut flour and; pearl millet-soybean paste (sour-dough technology used)	Millet-soybean sourdough bread showed higher ash and carbohydrate content compared to wheat bread	Okwunodulu *et al.*[127]
		Both sourdough breads had better levels of all studied micronutrients than wheat bread, except for iron	
		Loaf volume and specific loaf volume were enhanced only in millet-soybean sourdough bread compared to wheat bread	
		Dry matter, crude fiber, and energy content were superior in both sourdough breads compared to wheat bread	
	100% raw pearl millet flour	The bread made with a 50 : 50 blend of RMF (raw millet flour) and PCMF (pre-cooked pearl millet flour) had the highest specific volume, height, and uniform alveoli formation	Pessanha *et al.*[128]
		Bread with 100% RMF had the second-highest specific volume, while bread made with 100% PCMF had the lowest specific volume	
	Pre-cooked flour	The 50 : 50 RMF + PCMF bread exhibited the greatest softness	
		Higher amylose content in RMF may contribute to increased gas retention and bread volume	
	50 : 50 cooked and raw flour	Pearl millet (PCMF) shows potential for baking as a gluten substitute and provides antioxidant benefits	
	Foxtail millet	Enzyme-treated breads showed increased specific volume and crumb springiness	Sarabhai *et al.*[103]
		PR-treated bread had significantly reduced crumb hardness, chewiness, and cohesiveness compared to GO and XYL treatments	
	Enzyme used-glucose oxidase (GO), xylanase (XYL) and protease (PR)	PR-treated bread had higher sensory acceptability	
		Foxtail millet treated with PR enzyme resulted in improved physical and textural quality with higher acceptability	
	Amaranth flour (AF), buckwheat flour (BF), and quinoa flour (QF)	AF and QF have similar effects; BF provides higher consistency, improving bread structure and volume	Aguiar *et al.*[11]
		Blending with rice flour increases dough consistency, bread volume, softness, and acceptability	
		50% AF, BF, or QF with RF yields high acceptability	
Beverages	Beer produced using millet	Beverage samples exhibited a sour taste, lacked foam, and had a cider-like flavor and aroma	Dymchenko *et al.*[106]
	Roasted buckwheat (20 & 30%) as colourant	Sample which contained 30% roasted buckwheat, achieved the highest ratings for taste and coloration	
	Amylosubtilin bacterial enzyme used containing α-amylase	Unmalted gluten-free grains can also be used with added enzymes for full saccharification of the wort	
		The resulting product is more comparable to cider than beer	
Biscuits	CMC modified foxtail millet	Incorporating CMC into foxtail millet flour (FMF) improves biscuit development and quality	Reaz *et al.*[105]
		Adding up to 0.1% CMC hydrocolloid enhances the nutritional and sensory characteristics of the biscuits	
		The resulting biscuits are superior to commercial options due to lower fat content	

Table 6 (*Contd.*)

Products	Alternatives to wheat flour	Effects	Reference
Cookies	Buckwheat (10, 20, and 30%) in rice-based cookies	10–20% addition showed the highest overall acceptability like chewiness, flavour	Villaluenga *et al.*[7]
	Tartary buckwheat malt	Replaced 30% rice flour with tartary buckwheat malt in gluten-free cookies Higher content of total phenolics, quercetin, rutin, protein, fiber, and resistant starch Increased antioxidant activity, lower caloric value, and potential lower glycemic index compared to control cookies (RC and TFC)	Molinari *et al.*[104]
	Amaranth (raw and germinated)	Higher spread ratio observed than wheat-based cookies Cookies produced from germinated amaranth showed higher total dietary fiber and antioxidant activity and sensory attributes were acceptable	Villaluenga *et al.*[7]
Pasta	Buckwheat flour	Buckwheat flour (BWF) can be effectively combined with other gluten-free flours (maize and rice) to create dietetic pasta	De Arcangelis *et al.*[107]
	Maize and rice flour	Balanced formulations and appropriate technologies: using gelatinization and specific additives (0.1% PGA and 0.5% MFA) led to improved results compared to commercially available gluten-free pasta Best combination: gelatinized mixtures of BWF, maize flour (MF), and rice flour (RF) with the additives produced gluten-free pasta with excellent nutritional and cooking quality	
	Pearl millet flour Raw whole millet flour (RMF) and precooked millet flour (PCMF); formulations: 100% RMF and 50 : 50 RMF : PCMF	The 50 : 50 RMF : PCMF pasta showed better structural integrity, longer cooking time (8.5 min *vs.* 6.5 min), and improved texture compared with 100% RMF pasta. It also showed higher total phenolics (127.6 μmol GAE per g) and antihyperglycemic activity (99.5%). Compared with commercial brown rice pasta, it had higher protein (14.8%), lipid (8.1%), and fiber (7.0%), although acceptability was moderate (66%) due to texture limitations	Pessanha *et al.*[12]
Ready to eat products	Flakes from millets and pseudocereals	Amaranth and teff flakes exhibited the most favorable ratio of minerals to dietary fiber, phytates, and tannins Oat flakes are notable for magnesium (Mg) and iron (Fe), millet flakes for zinc (Zn), and rye flakes for magnesium (Mg), providing significant mineral content with acceptable levels of antinutrients Quinoa and spelt flakes have the potential for better mineral bioavailability but require technological processing to reduce antinutrient impacts on mineral content	Kiewlicz & Rybicka[13]

fermentation methods is required to improve sensory qualities, offering potential for gluten-free beer to cater to gluten-intolerant consumers.

Micro-malting experiments have shown that alkaline steeping enhances malt quality, making these grains suitable for brewing. Buckwheat beer exhibits similar properties to wheat beer in terms of pH, fermentability, and taste, while quinoa beer offers a unique nutritional advantage with a nutty flavor. Additionally, buckwheat contains bioactive constituents that make it suitable for the development of naturally gluten-free functional tea beverages. Buckwheat tea is generally produced through a sequence of processing steps in which raw seeds are soaked, steamed, dried, dehulled, and subsequently roasted to obtain tea-ready groats. These treatments contribute to the development of characteristic flavour and may influence the stability and availability of bioactive compounds.[67]

8.3 Gluten-free pasta and noodles

Buckwheat flour, either alone or in combination with maize and rice flour, has been effectively utilized to produce gluten-free pasta with enhanced nutritional and cooking qualities. The inclusion of 0.1% propylene glycol alginate and 0.5% monoglycerides of fatty acids, along with the gelatinization of flours, resulted in pasta with a high protein content (8.9–11.2% d.w.) and dietary fiber (8.9–14.4% d.w.). This makes the formulation particularly suitable for individuals with celiac disease. These optimized formulations and processing conditions improved the pasta's overall nutritional profile and cooking quality, surpassing that of commercially available gluten-free pasta.[107]

Additionally, Pessanha *et al.*[12] developed gluten-free pasta using raw whole millet flour (RMF) and precooked millet flour [PCMF; whole millet flour precooked by thermoplastic extrusion]. The 50 : 50 RMF : PCMF formulation showed better integrity, longer optimal cooking time (8.5 min *vs.* 6.5 min), and improved texture compared with 100% RMF pasta. It also exhibited higher antioxidant activity, total phenolics (127.6 μmol GAE per g), and antihyperglycemic activity (99.5%). Compared with commercial brown rice pasta, the millet pasta had higher protein (14.8%), lipid (8.1%), and fiber (7.0%) contents; however, its acceptability index was 66%, with texture remaining the main limitation.

8.4 Gluten-free breakfast and snack foods

Extrusion cooking, which combines high temperature, pressure, and mechanical shear, is widely used for manufacturing ready-to-eat breakfast cereals and snack products because it improves starch gelatinization, texture, digestibility, and shelf stability. In recent years, gluten-free pseudocereals and millets have gained increasing attention as extrusion ingredients due to their superior nutritional quality and suitability for individuals with coeliac disease and other gluten-related disorders. Breakfast cereals, particularly flakes and expanded extruded products, are important dietary sources of energy, dietary fiber, and essential micronutrients. Kiewlicz and Rybicka[13] reported that amaranth and teff flakes exhibited the most favorable mineral contribution among gluten-free cereals, particularly for magnesium and iron, nutrients frequently deficient in gluten-free diets. The authors further observed that amaranth and teff provided a more favorable balance between mineral content and antinutritional factors such as phytates and tannins, thereby improving their nutritional relevance. Oat flakes also contributed substantially to magnesium and iron intake, whereas millet and rye flakes were identified as good sources of zinc and magnesium, respectively.

Recent studies further support the incorporation of millets and pseudocereals in gluten-free breakfast cereal formulations. Caporizzi *et al.*[108] demonstrated that teff enrichment in rice-based gluten-free extruded breakfast cereals significantly improved protein, mineral, and dietary fiber contents while maintaining acceptable technological and microstructural properties. Similarly, Krishnan *et al.*[109] reported that pearl millet and finger millet blends could be successfully utilized in breakfast cereal production, resulting in improved nutritional quality and enhanced mineral composition compared with conventional cereal formulations. Acheampong *et al.*[110] also developed finger millet–maize composite breakfast cereals with desirable physicochemical and sensory properties along with improved nutritional attributes.

8.5 Gluten-free infant and complementary foods

Millets and pseudocereals can be used in gluten-free infant and complementary foods, including porridges, instant mixes, cereal–fruit blends, purees, and ready-to-cook formulations. Millet-based complementary foods are nutritionally relevant because processing methods such as milling, roasting, germination, fermentation, and extrusion can improve digestibility, reduce antinutritional factors, and enhance reconstitution and textural properties. Recent millet-based child food formulations have been reported to meet energy, protein, and iron requirements, although calcium content may require further improvement depending on the formulation.[111] Red millet has also been used with yellow maize and protein-rich ingredients to develop acceptable weaning foods with improved protein and mineral contents.[112]

Pseudocereals further improve the nutritional quality of infant foods due to their high-quality proteins, essential amino acids, minerals, vitamins, and bioactive compounds. Quinoa flour provides protein, iron, zinc, magnesium, and thiamine, although its phytate content may limit iron bioavailability if not properly processed. Amaranth contributes magnesium, calcium, phosphorus, iron, and zinc, while germinated amaranth flour can increase tocopherol levels but may reduce oxidative stability in baby purees. Buckwheat also supports dietary diversification due to its protein, minerals, and flavonoids.[85] Cereal-fruit formulations containing mango, banana, quinoa, and amaranth flour have shown promising nutritional, bioactive, and sensory potential, supporting the use of pseudocereals beyond single puree-based products.[113]

9 Consumer perception, adoption barriers, and market trends

Consumer acceptance is a key determinant of the successful commercialization of millet- and pseudocereal-based gluten-free foods. Although these grains are increasingly recognized for their nutritional value, gluten-free status, and sustainability potential, their regular consumption depends on consumer familiarity, sensory acceptability, convenience, affordability, product availability, and trust in health-related claims. For millets, consumer acceptance is influenced by perceived health value, sustainability awareness, food-choice habits, and availability of convenient millet-based products.[114] However, limited familiarity with millet preparation and lack of exposure to ready-to-use millet foods may discourage consumers from incorporating them into regular diets.[114] Several barriers limit wider adoption of millet-based foods. At the consumer level, unfamiliar taste, darker colour, coarse texture, longer cooking time, limited cooking knowledge, and the perception that millet foods are less convenient than rice- or wheat-based foods can reduce acceptance. At the market level, millet commercialization is constrained by supply-chain inefficiencies, limited consumer awareness, inconsistent policy support, insufficient processing infrastructure, and the need for better packaging, branding, and market diversification.[115] These barriers indicate that nutritional superiority alone is insufficient; millet-based products must also meet consumer expectations for taste, texture, convenience, and price.

Pseudocereals such as quinoa, amaranth, and buckwheat face related but slightly different adoption challenges. They are valued as gluten-free ingredients with high-quality proteins, dietary fiber, minerals, lipids, and bioactive compounds, and are increasingly used in bakery products, pasta, snacks, breakfast foods, and extruded formulations.[47] However, their broader incorporation into consumer products may be limited by higher raw-material cost, limited local availability, distinct flavour, darker colour, possible bitterness or astringency, and formulation-related challenges affecting texture and product structure. For example, amaranth and buckwheat have strong functional-food potential, but their successful use requires processing strategies that reduce antinutritional factors while improving sensory acceptability and maintaining nutritional quality.[116] Therefore, blending, fermentation, extrusion, enzymatic treatment, and hydrocolloid use may be required to improve consumer acceptability in gluten-free formulations.

Market trends are favourable for millet- and pseudocereal-based gluten-free foods because consumers are increasingly interested in ancient grains, plant-based foods, sustainable diets, functional ingredients, and nutrient-dense gluten-free products. The global millet market is gaining attention due to health and sustainability movements and international initiatives such as the International Year of Millets; however, market growth still depends on improved value chains, stable raw-material supply, consumer education, product standardization, and stronger links between farmers, processors, and retailers.[115] Pseudocereals are also gaining relevance as climate-resilient and gluten-free crops with applications in baked, fermented, and extruded foods.[117] Thus, future product development should combine sensory optimization, affordability, shelf-life assessment, packaging design, clear nutritional labelling, consumer education, and market-positioning strategies to improve the adoption of millet- and pseudocereal-based gluten-free foods.

10 Conclusion

Millets and pseudocereals offer promising alternatives for improving gluten-free nutrition, particularly for individuals with gluten-related disorders. Compared with many refined starch-based gluten-free products, these grains provide better nutritional quality through higher levels of protein, essential amino acids, dietary fiber, minerals, vitamins, and bioactive compounds. Processing methods such as soaking, germination, fermentation, puffing, popping, milling, and extrusion further enhance their value by reducing antinutritional factors, improving digestibility and nutrient bioavailability, and supporting the development of diverse gluten-free products, including bakery products, pasta, snacks, beverages, and infant foods. Beyond nutrition, these grains also contribute to sustainable food systems. Millets are especially relevant as climate-resilient crops due to their lower water and input requirements, reduced carbon footprint, and suitability for marginal agro-climatic conditions. Pseudocereals such as quinoa, amaranth, and buckwheat further strengthen gluten-free formulations by contributing high-quality proteins, unsaturated fatty acids, minerals, and phytochemicals.

However, several knowledge gaps remain. Future research should focus on grain-specific optimization of processing conditions, as millets and pseudocereals differ in starch structure, protein composition, antinutrient profile, phenolic content, and functional behavior. Standardized protocols for soaking, germination, fermentation, roasting, puffing, popping, and extrusion are needed to maximize nutrient retention, reduce antinutrients, improve sensory quality, and minimize process-induced contaminants such as acrylamide. In addition, industrial-scale feasibility studies are required to assess raw material availability, processing cost, shelf stability, packaging requirements, consumer acceptance, and market competitiveness. Future studies should evaluate the production cost, environmental impact, and health effects of millet- and pseudocereal-based gluten-free products to support their large-scale commercial application.

Author contributions

Amisha kaushik: writing – original draft, formal analysis. D. C Saxena: writing – review & editing, conceptualization, validation, visualization, supervision. Sukhcharn Singh: review & editing, conceptualization, validation, visualization, supervision.

Conflicts of interest

The author declares no conflicts of interest.

Data availability

The data of this study are available upon request.

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