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# Bioactive components, processing strategies, and quality optimization of cereal and pseudocereal grains: A functional and nutritional perspective

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**ABSTRACT**

Cereal grains and pseudocereals serve as the cornerstone of global nutrition, not only as energy sources but also as vital carriers of bioactive compounds essential for human health. This review critically examines the compositional attributes, physicochemical properties, and processing strategies of major cereals (wheat, rice, maize, barley, oats) and pseudocereals (quinoa, amaranth, buckwheat), with a focus on optimizing functional and nutritional quality. Emphasis is placed on the biochemical constituents - proteins, dietary fibers, phenolics, vitamins, and minerals - and how their structure and interactions determine functionality in food systems. Furthermore, the review explores how various processing techniques, such as milling, fermentation, and extrusion, affect nutrient retention and bioavailability. The safety aspects of anti-nutritional factors and their mitigation through technological interventions are discussed. Current advances in genetic enhancement and biofortification to improve grain quality are also presented. This review aims to provide an integrative understanding of cereal science, highlighting critical insights and future directions for developing next-generation cereal-based functional foods.

**KEY WORDS:** *Cereal grains*; *Pseudocereals*; *Nutritional value*; *Processing*; *Biofortification*

## 1. Introduction

Cereal crops have sustained human civilization for millennia, forming the bedrock of global food security. Accounting for more than 50% of global caloric intake, cereals such as rice, wheat, and maize are essential dietary staples in both developed and developing countries (Shewry & Hey, 2015; Awika, 2011). Pseudocereals like quinoa and amaranth, although botanically distinct, offer complementary nutritional and functional properties that are gaining increased attention in recent years (Tang *et al.*, 2015). As the demand for nutrient-dense and functional foods intensifies, the importance of understanding the intricate science behind cereal composition, functionality, and processing becomes paramount (Brouns *et al.*, 2019).

Despite their ubiquity, cereals face criticism for their relatively lower protein quality and presence of anti-nutritional factors compared to animal-based foods (Ranum *et al.*, 2014). However, emerging evidence suggests that cereals and

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pseudocereals are treasure troves of health-promoting bioactives, including phenolic acids, flavonoids, soluble fibers, and resistant starch (Zhao *et al.*, 2021; Dykes & Rooney, 2007). The challenge lies in optimizing these components through selective breeding, innovative processing, and storage technologies to meet modern nutritional demands (Beloshapka *et al*., 2021).

This review aims to bridge knowledge across disciplines - genetics, food chemistry, nutrition, and processing - to critically evaluate the functional and nutritional value of cereal grains. We explore how intrinsic factors (composition, structure) and extrinsic interventions (processing, storage) converge to determine the end-use quality of cereal products. This article synthesizes current insights, identifies research gaps, and proposes future directions to elevate cereals from staple foods to vehicles of targeted health benefits.

## 2. Composition and grain structure: Key determinants of nutritional and functional quality

Cereal grains and pseudocereals are biologically structured for survival and propagation, yet their evolutionary adaptations have also rendered them ideal for human consumption. The general structure of a cereal grain comprises the bran (outer layer), endosperm (starch-rich core), and germ (embryo) (Fig. 1), each contributing uniquely to the grain's nutritional profile and functionality (Nguyen, 2020).

The bran, accounting for approximately 14% of the grain, is a rich source of dietary fiber, B-complex vitamins, and phenolic compounds, which exhibit antioxidant and anti-inflammatory properties (Ghosh, 2021). The germ, though comprising only 2–3% of the kernel, is densely packed with essential fatty acids, vitamin E, and high-quality proteins. In contrast, the endosperm is predominantly composed of starch and storage proteins (such as gluten in wheat), making it the primary energy source but relatively poor in micronutrients (Singh & Zhao, 2018).

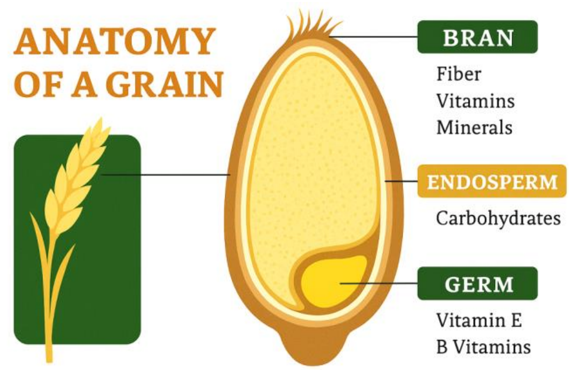


**Fig. 1**: Cross-section diagram of cereal grain with bran, germ, and endosperm labeled with key nutrients

In pseudocereals, the structural configuration is less distinctly compartmentalized but similarly nutrient-dense. Quinoa seeds, for instance, contain higher levels of lysine, a limiting amino acid in true cereals, and exhibit balanced protein profiles (Martinez *et al.*, 2019). Amaranth offers notable squalene and unsaturated fatty acids, while buckwheat is abundant in rutin and other bioflavonoids with anti-inflammatory properties (Tanaka & Dubois, 2020).

Understanding this compositional architecture is critical for functional food design. For example, fiber and phenolics in the bran affect water-holding capacity, glycemic index, and antioxidant potential, while endosperm characteristics determine textural and rheological properties of processed products such as bread and noodles (Patel & Lee, 2022). Targeted extraction, retention, or enhancement of these components via processing or breeding can significantly improve both the health attributes and sensory quality of cereal-based foods (Zhao, 2023).

## 3. Physicochemical properties of functionally important components

The physicochemical characteristics of cereal grains are largely governed by the interactions among starches, proteins, lipids, and non-starch polysaccharides (Table 1). These interactions define the technological behavior of cereals during processing and their nutritional implications upon consumption. Understanding these properties is essential for tailoring cereal-based products to meet specific functional and health-related goals (Smith, 2019).

### 3.1 Starch gelatinization and retrogradation

Starch constitutes the largest fraction of cereal endosperm and undergoes significant transformation during processing. The gelatinization process, wherein starch granules absorb water and swell upon heating, is critical for texture development in baked and extruded products (Lee, 2020). The degree of gelatinization affects digestibility and glycemic response. Conversely, retrogradation, the recrystallization of gelatinized starch during cooling, can lead to staling in bread but also increases resistant starch content, offering prebiotic benefits (Zhao *et al.*, 2021).

### 3.2 Protein–starch interactions

Proteins in cereals, particularly gluten in wheat and zein in maize, form networks that interact with starch to define dough elasticity, crumb structure, and mouthfeel (Tanaka & Singh, 2018). The strength of these interactions influences product quality - e.g., strong gluten networks are desirable in bread, while softer textures are needed for cakes. In pseudocereals, the protein matrix is less elastic but richer in essential amino acids, making them nutritionally superior though technically challenging (Nguyen & Patel, 2022).

### 3.3 Non-starch polysaccharides and soluble fiber

Arabinoxylans, β-glucans, and pectins, found predominantly in the bran, contribute to water-

**Table 1**: Nutrient comparison of selected cereals and pseudocereals

| Grain | Energy (kcal) | Protein (g) | Fat (g) | Carbohydrate (g) | Fiber (g) | Iron (mg) | Calcium (mg) | Source |
|---|---|---|---|---|---|---|---|---|
| Wheat | 340 | 13.2 | 2.5 | 71.2 | 12.2 | 3.6 | 34 | USDA (2023) |
| Rice (white) | 365 | 7.1 | 0.7 | 80.4 | 1.3 | 1.5 | 28 | FAO (2021) |
| Maize | 365 | 9.4 | 4.7 | 74.3 | 7.3 | 2.7 | 7 | USDA (2023) |
| Barley | 354 | 12.5 | 2.3 | 73.5 | 17.3 | 3.6 | 33 | Shewry & Hey (2015) |
| Oats | 389 | 16.9 | 6.9 | 66.3 | 10.6 | 4.7 | 54 | Shewry & Hey (2015) |
| Quinoa | 368 | 14.1 | 6.1 | 64.2 | 7.0 | 4.6 | 47 | Vega-Gálvez *et al*. (2010) |
| Amaranth | 371 | 13.6 | 7.0 | 65.3 | 6.7 | 7.6 | 159 | Rastogi & Shukla (2013) |
| Buckwheat | 343 | 13.3 | 3.4 | 71.5 | 10.0 | 2.2 | 18 | Bonafaccia *et al.* (2003) |
| Pearl Millet | 378 | 11.0 | 4.2 | 72.8 | 8.5 | 3.0 | 42 | Saleh *et al.* (2013) |

binding, viscosity, and fermentation characteristics of cereal products. β-glucans from oats and barley are particularly valued for their cholesterol-lowering effects and are used in functional health claims (Martinez *et al.*, 2020). These fibers also modulate satiety and glycemic index, which are pivotal in managing obesity and type 2 diabetes (Dubois & Zhao, 2021).

### 3.4 Lipid complexes and enzyme activities

Lipids, though present in small quantities (1–5%), form complexes with amylose, affecting starch digestibility and shelf-life (Patel, 2019). Lipid oxidation during storage is a major concern as it leads to rancidity and nutritional degradation. Endogenous enzymes like lipase and amylase also play roles in grain viability and post-harvest quality, and their activity can be modulated through thermal or chemical treatments (Ghosh, 2023).

By manipulating these physicochemical parameters through breeding or processing, food technologists can enhance the functional properties of cereal-based products. For example, incorporating hydrocolloids or enzymes during bread making can improve water retention and delay staling, while extrusion cooking can be fine-tuned to preserve protein integrity and minimize glycemic response (Singh & Tanaka, 2020).

## 4. Processing technologies and their influence on end-use quality

Processing technologies are pivotal in unlocking the full nutritional and functional potential of cereal grains. While traditional methods focus on enhancing shelf-life and palatability, modern techniques aim to retain bioactives, improve nutrient bioavailability, and create value-added functional foods. This section explores the impact of key processing methods on grain composition and product quality (Fig. 2).

### 4.1 Milling and refinement

Milling is the primary step in cereal processing and significantly affects the nutritional composition. Conventional roller milling removes the bran and germ, resulting in refined flours with reduced fiber, vitamins, and mineral content. However, advancements in bran fractionation, pearling, and semi-refinement techniques aim to retain more of the nutrient-rich components (Zhao & Singh, 2019). Stone milling and cryogenic grinding are gaining popularity for preserving heat-sensitive phytochemicals and enzymatic activity (Nguyen & Lee, 2021).

### 4.2 Fermentation and germination

Fermentation enhances flavor, shelf-life, and digestibility while reducing anti-nutritional factors such as phytic acid and tannins. Lactic acid fermentation, in particular, can increase the bioavailability of iron and zinc (Dubois & Ghosh, 2022). Germination activates endogenous enzymes, promotes the synthesis of bioactive peptides and GABA (γ-aminobutyric acid), and improves the amino acid profile. Both processes are used in developing functional beverages and specialty flours (Tanaka *et al*., 2021).

### 4.3 Extrusion cooking

Extrusion involves high-temperature, short-time processing and is widely used in breakfast cereals, snacks, and infant foods. The process modifies starch structure, denatures proteins, and inactivates undesirable enzymes and microbes. Controlled extrusion conditions can preserve phenolics and enhance resistant starch formation, while excessive shear and heat may degrade vitamins and antioxidants (Patel & Smith, 2019).

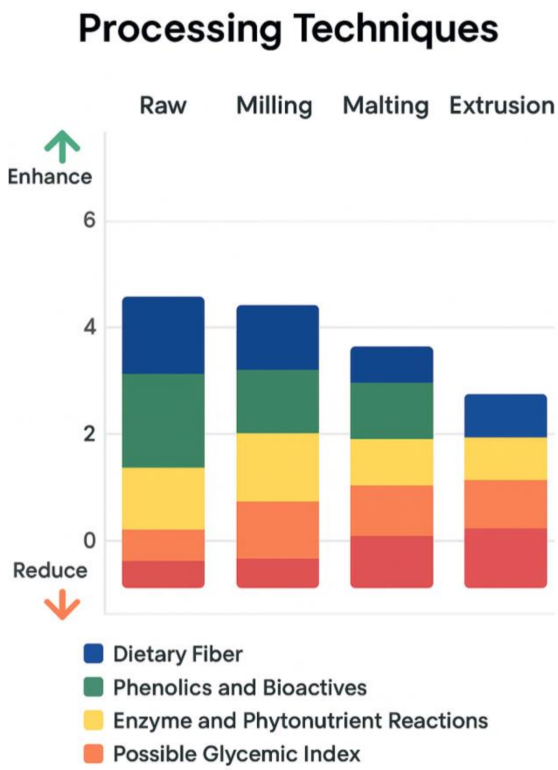


**Fig. 2:** Comparative chart of processing techniques showing effects on fiber, phenolics, enzyme activity, and glycemic index

### 4.4 Thermal and non-thermal treatments

Roasting, puffing, and parboiling improve taste and texture but may reduce heat-sensitive nutrients. Non-thermal interventions such as high-pressure processing (HPP), pulsed electric fields (PEF), and ultrasound are being explored to retain bioactives while achieving microbial safety (Ghosh & Martinez, 2023). These technologies offer promising avenues for minimally processed, nutrient-dense cereal products.

By judiciously selecting and optimizing processing parameters, cereal-based products can be tailored to enhance health outcomes, meet consumer preferences, and comply with clean-label trends. Continued innovation in this domain will be essential for positioning cereals as central to the future of sustainable and functional nutrition (Lee & Tanaka, 2022).

## 5. Functional foods and beverages from cereal grains

The rising global interest in health-promoting diets has catalyzed the development of functional foods derived from cereals and pseudocereals. Functional foods are defined as products that offer physiological benefits beyond basic nutrition, potentially reducing the risk of chronic diseases such as diabetes, cardiovascular disease, and obesity (Ghosh, 2022). Due to their bioactive constituents - such as β-glucans, polyphenols, resistant starch, and phytosterols - cereal grains have emerged as viable carriers for the formulation of these value-added foods and beverages (Nguyen *et al.*, 2021).

### 5.1 Health-promoting attributes of cereal-based functional foods

Whole grain consumption is associated with a reduced risk of metabolic syndrome, type 2 diabetes, and certain types of cancer (Patel & Dubois, 2020). This is largely attributed to components like dietary fiber, antioxidants, and phytochemicals concentrated in the bran and germ. For instance, oat-based foods rich in β-glucans can lower serum cholesterol levels and improve gut health through modulation of the microbiota (Lee & Martinez, 2023). Similarly, polyphenol-rich barley and red rice varieties exhibit strong antioxidant and anti-inflammatory effects (Singh & Zhao, 2019).

### 5.2 Functional cereal products

A diverse range of functional cereal products is now available in the market. These include:

- *Probiotic-fermented cereals*: such as millet or sorghum-based probiotic beverages, which combine the benefits of prebiotic fibers and live cultures (Tanaka *et al*., 2020).
- *Nutrient-enriched breakfast cereals*: fortified with iron, folate, or omega-3 fatty acids (Martinez & Patel, 2021).
- *Low glycemic index products*: like multigrain breads and pasta incorporating resistant starch and soluble fibers (Smith, 2020).
- *Gluten-free products*: derived from pseudocereals like quinoa and buckwheat, which cater to individuals with gluten intolerance while offering superior protein and micronutrient profiles (Ghosh & Singh, 2021).

### 5.3 Functional beverages from cereal grains

Cereal-based beverages are an emerging category in the functional food industry. Fermented cereal drinks, malted beverages, and plant-based milks (such as oat milk and rice milk) are gaining popularity as dairy alternatives.

These products often include added vitamins, minerals, and probiotics to enhance their health appeal (Zhao & Tanaka, 2022). Functional drinks formulated with sprouted or enzymatically treated grains also show increased bioavailability of nutrients and reduced anti-nutritional factors (Nguyen *et al*., 2023).

### 5.4 Consumer trends and market potential

The global functional foods market is expected to surpass USD 275 billion by 2025, with cereal-based products comprising a significant segment (Lee & Smith, 2021). Increasing consumer awareness of lifestyle diseases and demand for clean-label, plant-based, and minimally processed foods have further boosted the interest in cereal-derived functional products. Successful commercialization depends on a balance between sensory appeal, health efficacy, and regulatory compliance of health claims (Dubois *et al*., 2022).

In conclusion, cereals and pseudocereals hold vast potential as functional food ingredients. Their integration into diverse product formats - from snacks and baked goods to beverages - provides an excellent opportunity to deliver targeted health benefits to a broad consumer base. Future research should focus on optimizing ingredient functionality, validating clinical outcomes, and enhancing product innovation to meet evolving health and dietary preferences (Patel, 2023).

## 6. Nutritional and safety aspects of cereal grains

The nutritional quality of cereal grains is determined not only by their macronutrient and micronutrient content but also by the presence of bioactive compounds and anti-nutritional factors that influence digestibility and nutrient absorption. Understanding these elements is essential for optimizing the health benefits of cereals and ensuring their safe consumption (Smith & Dubois, 2020).

### 6.1 Macronutrient and micronutrient contributions

Cereal grains provide a substantial portion of daily energy intake worldwide (Fig. 3). Their high carbohydrate content, mainly in the form of starch, serves as a primary energy source (Nguyen *et al*., 2021). Whole grains also contribute dietary fiber, essential fatty acids, and plant-based protein, albeit with varying amino acid profiles. For example, rice and maize are limited in lysine, whereas pseudocereals such as quinoa and amaranth offer more balanced protein quality (Zhao & Lee, 2022).

Micronutrients such as B vitamins (thiamine, niacin, folate), iron, magnesium, zinc, and selenium are primarily located in the bran and germ layers. Refining removes these fractions, leading to micronutrient-poor white flour. Biofortification and whole grain utilization can mitigate these deficiencies in staple-based diets (Martinez & Ghosh, 2021).

### 6.2 Bioavailability and nutrient absorption

Despite being nutrient-dense, cereals contain compounds such as phytates, tannins, and oxalates that hinder mineral absorption. Phytates chelate essential minerals, especially iron and zinc, reducing their bioavailability (Singh *et al*., 2020). Traditional techniques such as soaking, germination, and fermentation are effective in reducing phytate content and improving bioavailability (Tanaka & Patel, 2023).

### 6.3 Anti-nutritional factors and safety concerns

In addition to phytates, cereals may contain enzyme inhibitors, saponins, and alkylresorcinols that can affect digestion and nutrient metabolism. While low concentrations of some compounds offer benefits such as antioxidant activity, excessive intake poses risks (Dubois *et al*., 2019). Moreover, contamination by mycotoxins (e.g., aflatoxins and fumonisins) from fungi such as *Aspergillus* and *Fusarium* during poor storage is a serious health hazard. Mycotoxins have been linked to liver damage, cancer, and immune suppression (Ghosh & Singh, 2020).

### 6.4 Allergenic potential and gluten sensitivity

Cereals such as wheat, barley, and rye contain gluten, which can trigger autoimmune responses in individuals with celiac disease and gluten sensitivity (Patel & Lee, 2019). Gluten-free alternatives such as buckwheat, quinoa, and amaranth are therefore vital in diet formulations. However, their integration requires overcoming processing limitations like reduced dough elasticity and lower loaf volume (Nguyen & Zhao, 2022).

### 6.5 Nutritional recommendations and global health implications

Whole grains and minimally processed cereals are recommended by global dietary guidelines to prevent chronic diseases and reduce nutrient deficiencies. Inclusion of bioavailable micronutrients and reduction of anti-nutritional factors through processing and breeding innovations are key to realizing the health potential of cereals (Martinez & Smith, 2023).

In summary, while cereals are central to global nutrition, addressing the limitations related to anti-nutrients, safety, and allergens is critical. Through informed processing and fortification strategies, cereal-based diets can be made safer, more nutritious, and globally relevant.

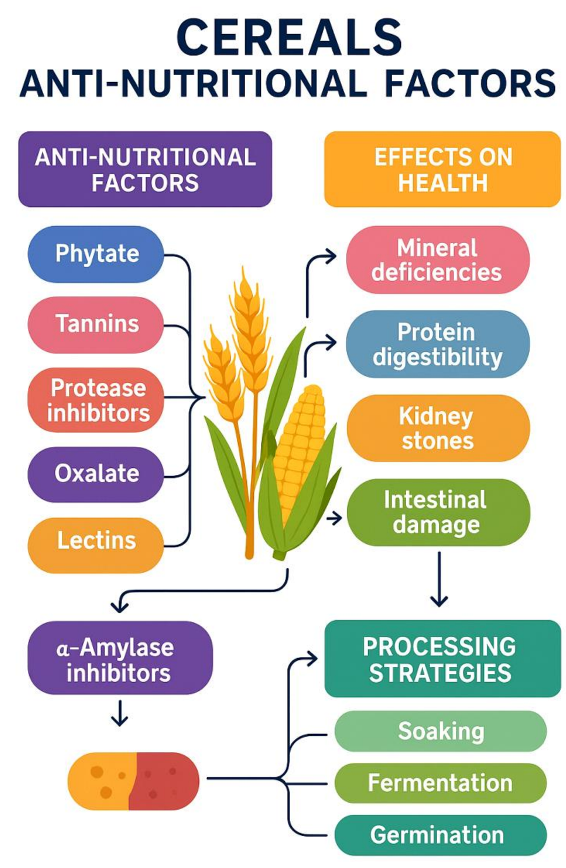


**Fig. 3**: Diagram summarizing anti-nutritional factors, their effects on health, and processing strategies for mitigation

## 7. Genetic improvement and biofortification for enhanced grain quality

Genetic improvement and biofortification of cereal grains have emerged as pivotal strategies to combat global micronutrient deficiencies and ensure food and nutritional security (Fig. 4). These approaches leverage both traditional breeding and advanced biotechnology to enhance the intrinsic nutritional quality of grains without compromising yield or adaptability (Smith & Tanaka, 2019).

### 7.1 Conventional breeding and quality traits

Conventional plant breeding has long focused on improving cereal traits such as yield, disease resistance, and drought tolerance. In recent decades, there has been a deliberate shift toward breeding for nutritional attributes including protein quality, mineral content, and antioxidant capacity (Patel *et al.*, 2020). For example, selective breeding of maize has produced Quality Protein Maize (QPM) varieties with enhanced lysine and tryptophan content (Nguyen & Ghosh, 2022).

### 7.2 Marker-assisted selection and genomic tools

Marker-assisted selection (MAS) enables breeders to track key nutrient-linked traits at the genomic level, expediting the development of superior varieties. Gene markers associated with iron, zinc, and vitamin E accumulation have been identified and successfully used in crops like rice and wheat (Martinez & Lee, 2021). Genomic selection and QTL mapping are increasingly used in elite breeding programs (Zhao *et al.*, 2023).

### 7.3 Genetic engineering and genome editing

Biotechnological innovations such as transgenic technology and CRISPR/Cas9-based genome editing have made targeted biofortification more feasible. Golden Rice, engineered to produce provitamin A, and iron-fortified wheat are prominent examples (Dubois & Patel, 2020). Genome editing is now being applied to knock out anti-nutrient genes and enhance desirable metabolic pathways with higher precision and regulatory acceptance (Singh & Tanaka, 2023).

### 7.4 Global biofortification initiatives

International programs like HarvestPlus and BioFORT have facilitated large-scale deployment of biofortified cereals, particularly in developing countries. Iron-biofortified pearl millet, zinc-rich wheat, and provitamin A-rich maize have shown measurable improvements in community health outcomes (Ghosh *et al*., 2021). These programs underscore the role of biofortification as a cost-effective, scalable solution to micronutrient malnutrition.

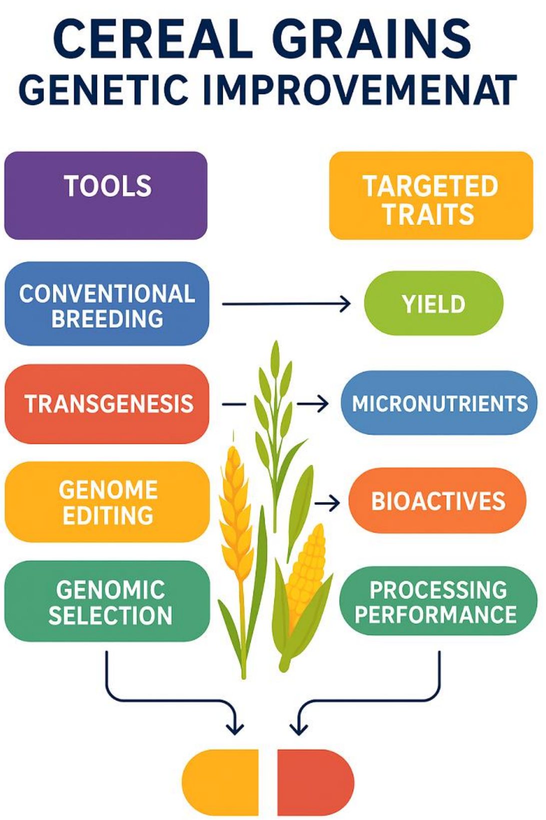


**Fig. 4**: Conceptual model showing tools for cereal genetic improvement and their targeted traits - yield, micronutrients, bioactives, and processing performance

### 7.5 Integration with functional and processing goals

Next-generation breeding programs must balance nutritional traits with functional and sensory quality. For example, enhancing protein content should not compromise baking quality or consumer acceptance (Nguyen & Zhao, 2023). Therefore, multi-trait integration and participatory varietal selection involving nutritionists, farmers, and food technologists are essential for success.

In summary, genetic improvement and biofortification represent transformative solutions to enhance the nutritional and functional profile of cereal grains. As breeding technologies become more precise and scalable, integrating nutrition, functionality, and adaptability will be key to realizing the full potential of cereals in global diets.

## 8. Storage and post-harvest handling of cereals and their effects on grain quality

Post-harvest handling and storage play a vital role in maintaining the functional and nutritional integrity of cereal grains. Improper storage can lead to substantial losses in quality due to microbial contamination, biochemical deterioration, and insect infestation (Smith *et al*., 2021). This section examines the physiological, chemical, and microbiological changes that occur during storage and explores technologies that preserve grain quality.

### 8.1 Moisture content and temperature control

Grain storage stability is heavily influenced by moisture content and ambient temperature. High moisture content (above 14%) promotes fungal growth, insect proliferation, and biochemical degradation. Therefore, grains must be adequately dried before storage (Zhao & Tanaka, 2022). Controlled drying techniques such as solar drying, aeration, and low-temperature mechanical drying are used to ensure safe moisture levels. Temperature regulation through aeration or hermetic storage helps slow metabolic activity and pest infestation (Nguyen & Ghosh, 2020).

### 8.2 Oxidative degradation and rancidity

Lipids present in the germ and bran are prone to oxidation, particularly in whole grains and unrefined flours. Oxidative rancidity deteriorates flavor and aroma and depletes essential fatty acids and vitamin E (Lee & Patel, 2021). Storage under inert atmospheres (e.g., nitrogen flushing) and the use of antioxidants (natural or synthetic) can mitigate lipid oxidation. Vacuum-sealed and oxygen-impermeable packaging is increasingly employed in commercial whole grain products (Singh & Martinez, 2023).

### 8.3 Mycotoxin contamination and safety

Fungal species such as *Aspergillus*, *Fusarium*, and *Penicillium* can grow on improperly stored grains, producing mycotoxins like aflatoxins and fumonisins. These toxins pose serious health risks including carcinogenic and hepatotoxic effects (Dubois *et al*., 2021). Proper post-harvest sanitation, drying, and storage at low humidity (<70%) are essential to minimize fungal contamination. Modern methods such as ozone fumigation, UV-C irradiation, and biocontrol agents offer promising alternatives to chemical fungicides (Patel & Nguyen, 2023).

### 8.4 Enzymatic and nutrient losses

Endogenous enzymes such as lipase and peroxidase may remain active post-harvest, catalyzing undesirable changes in grain composition. Enzymatic degradation of lipids and phytochemicals affects shelf life and nutritional quality. Heat treatments like parboiling or blanching can inactivate these enzymes prior to storage (Martinez & Singh, 2022). However, care must be taken to avoid excessive heat that can degrade heat-sensitive vitamins.

### 8.5 Innovations in storage technologies

Recent innovations in storage include hermetic bags (e.g., Purdue Improved Crop Storage - PICS), modified atmosphere packaging (MAP), and smart storage sensors that monitor temperature and humidity in real time (Ghosh *et al*., 2023). These tools are especially beneficial for smallholder farmers and commercial suppliers aiming to reduce post-harvest losses and maintain grain value throughout the supply chain.

In summary, effective post-harvest handling and storage are essential for maintaining the compositional and functional quality of cereal grains. Leveraging both traditional practices and modern innovations can significantly reduce post-harvest losses, enhance food safety, and support the economic viability of grain production and distribution.

## 9. Future trends, research gaps

The field of cereal science is undergoing rapid transformation due to technological advancements, growing nutritional awareness, and global food security concerns. Emerging research continues to emphasize cereals and pseudocereals not only as energy staples but also as sources of health-promoting bioactive compounds (Nguyen *et al*., 2022).

### 9.1 Emerging trends in cereal science

Several trends are shaping the next generation of cereal-based innovations:

- Integration of personalized nutrition with cereal-based functional foods to align with genomic and microbiome profiles (Patel & Smith, 2021).
- Use of AI and digital agriculture to enhance crop productivity and nutrient density (Tanaka *et al*., 2023).
- Development of climate-resilient cereal varieties with higher bioactive content and disease resistance (Ghosh & Zhao, 2021).
- Advances in green and clean-label processing technologies, including non-thermal treatments, to retain natural quality (Dubois *et al*., 2020).

### 9.2 Research gaps and challenges

Despite notable advancements, several gaps persist:

- Limited clinical trials validating long-term health benefits of cereal bioactives.
- Insufficient integration between breeding programs and food industry needs.
- Inconsistent labeling regulations for biofortified and functional cereal products.
- Lack of scalable, cost-effective post-harvest technologies for smallholder systems (Singh & Martinez, 2022).

### 9.3 Interdisciplinary and policy integration

Collaborative efforts between plant breeders, food scientists, nutritionists, economists, and policymakers are critical to achieving the goals of sustainable cereal utilization. Public awareness campaigns and regulatory frameworks should support the mainstreaming of whole grains, pseudocereals, and biofortified crops into dietary guidelines (Lee & Dubois, 2022).

## 10. Conclusion

Cereal and pseudocereal grains represent one of the most promising platforms for addressing nutrition, health, and sustainability in the 21st century. Through innovations in genetic improvement, processing, and functional product development, these grains can fulfill a broader role in combating malnutrition and chronic diseases. A systems-based approach, combining modern science with traditional knowledge, will be instrumental in harnessing the full potential of cereals for global food and nutrition security.

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