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***REVIEW ARTICLE***

# Black Wheat as a Biofortified Cereal: Nutritional Composition, Anthocyanin Content, and Functional Food Applications

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## ABSTRACT

Black wheat offers a significant improvement in cereal biofortification, providing a nutritionally rich alternative to regular wheat by combining better macronutrient quality with a strong bioactive chemical profile. This type, developed by standard hybridization, is distinguished by its rich coloration, which is due to substantial anthocyanin deposition in the bran and aleurone layers, reaching values 20 to 30 times greater than those found in typical white wheat. Its nutritional profile is distinguished by greater protein quality with balanced amino acids, enhanced dietary fibre, and higher quantities of key minerals including iron, zinc, and selenium. Functionally, black wheat has a much greater antioxidant capacity (DPPH inhibition of 70-80%) and a lower glycaemic index (GI 45-50), which contributes to better metabolic management, anti-inflammatory properties, and intestinal health. These characteristics, combined with its high thermal stability during processing, have enabled its successful incorporation into a wide range of functional food applications, including bread, chapatti, noodles, and fermented products, effectively bridging the gap between traditional diets and modern health requirements.

**Key words:** Black wheat, biofortification, anthocyanins, nutritional quality, antioxidant activity, functional foods, glycemic index

## INTRODUCTION

Wheat (*Triticum aestivum* L.) is one of the world's most widely grown cereal crops, accounting for almost 20% of total dietary caloric and protein consumption (Abdullah et al., 2025; Ullah et al., 2024a). Wheat is a member of the Poaceae family, and its tolerance to varied agro-climatic zones, high yield potential, and processing flexibility make it essential for both industrial and home food production. Traditional wheat has around 70-72% carbs, 11-13% protein, 1.5-2% fat, and 2-3% minerals (Singh et al., 2023; Ullah et al., 2024b). Nonetheless, despite their worldwide relevance, standard wheat cultivars have relatively low amounts of critical micronutrients including iron (25-35 mg/kg) and zinc (20-30 mg/kg), as well as restricted antioxidant chemicals. This nutritional shortage has sparked scientific interest in biofortified wheat cultivars, which are intended to improve both micronutrient density and bioactive chemical content in order to combat malnutrition and chronic illnesses in humans (Sharma et al., 2025).

To fulfil the increased demand for nutrient-rich cereals, the National Agri-Food Biotechnology Institute (NABI) in Mohali, India, created black wheat as part of India's cereal biofortification initiative. This variety was created using traditional hybridization, in which high-

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anthocyanin donor lines from Triticum turgidum were crossed with elite T. aestivum cultivars with no genetic change (Dwivedi et al., 2022). The grain's dark to deep purple color results from a high concentration of anthocyanins in the pericarp and aleurone layers, which act as natural antioxidants and contribute to its exceptional nutritional and functional value. Black wheat has a total anthocyanin level of 100 to 140 mg cyanidin-3-glucoside equivalents per 100 g, compared to less than 5 mg/100 g in regular whole wheat (Parizad, 2018). The most common anthocyanin molecules are cyanidin-3-glucoside (45-55%), delphinidin-3-glucoside (20-25%), and peonidin-3-glucoside (10-15%), which together improve antioxidant and anti-inflammatory capabilities. Furthermore, black wheat has 2-3 times greater total phenolic content and 1.5-2 times more ferric-reducing antioxidant potential than typical wheat cultivars (Liu et al., 2021). Black wheat has an average protein composition of 12-14%, which is somewhat greater than that of whole wheat (10-12%), with an enhanced amino acid balance, including higher amounts of lysine (3.8-4.2 g/100 g protein) and tryptophan (1.2-1.4 g/100 g protein) (Sadowska-Bartosz et al., 2024). Mineral analysis shows iron content of 45 to 55 mg/kg, zinc content of 40-50 mg/kg, and magnesium content of 1.2-1.5 g/kg, which is much higher than traditional wheat levels (Wysocka et al., 2025). Black wheat has more dietary fibre (11-13%) than whole wheat (9-10%), which leads to better gut health and a lower glycaemic response.

From a nutritional standpoint (Table 1; Figure 1), black wheat is a multifunctional grain that efficiently links traditional dietary habits with modern health needs. Its antioxidant capacity (DPPH inhibition (70-80%) is much higher than that of regular wheat (25-30%). Furthermore, its glycaemic index (GI 45-50) is significantly lower than that of whole wheat (GI 70-75), making it ideal for diabetics and health-conscious people (Jimenez-Pulido et al., 2022). Black wheat has a greater β-glucan content (1.1-1.4 g/100 g), which helps lower cholesterol and improve cardiovascular health. The anthocyanins and polyphenols found in black wheat are thermally stable up to 160-180°C, allowing for their excellent inclusion into bread and fermented food items with minimal loss of bioactivity (Borczak et al., 2021). Further study showed that consuming 100 g of black wheat flour daily might increase plasma antioxidant activity by 30-40% while decreasing oxidative indicators in vivo.

## MATERIALS AND METHODS

### 2. Nutritional Properties of Black Wheat

### 2.1 Starch and Other Carbohydrates

Wheat's starch is mostly composed of amylose, a linear polymer with a low molecular weight of $10^5$-$10^6$, and amylopectin, a highly branched polymer with a significantly higher molecular weight of $10^7$-$10^8$. These polymers produce semi-crystalline starch granules in the endosperm, which are held together by hydrogen bonds between radially orientated glucan chains (Waduge et al., 2014). Starch functionality gelatinisation, pasting behaviour, and enzymatic digestibility is mostly determined by the amylose-to-amylopectin ratio, which accounts for 98-99% of the dry starch weight, with minimal lipid interactions. Higher amylose content often promotes resistant starch production and longer digestion, resulting in lower postprandial glycaemic responses (Waduge et al., 2012). Starch digestibility is further affected by granule size, protein-starch interactions, and non-starch components dietary fibre and lipids that limit enzyme accessibility (Khatun et al., 2019). Starch can be classed as immediately digestible, slowly digestible, or resistant starch. The latter is digested in the colon to create health-promoting short-chain fatty acids SCFAs (Šárka et al., 2024). Targeted manipulation of starch biosynthetic enzymes has been demonstrated to boost amylose and resistant starch levels, potentially improving wheat's nutritional quality and processing functionality (Kim et al., 2021). Furthermore, metabolomic investigations of wheat types, including black wheat, revealed a diversified carbohydrate profile with a much greater polysaccharide content than normal wheat. This metabolic complexity may add to variances in starch functioning, digestibility, and related health advantages (Adegoke et al., 2021).

### 2.2 Dietary Fiber

Wheat dietary fibre is mostly made up of nondigestible polysaccharides (cellulose, hemicellulose, pectin, and resistant starch), which are not hydrolysed by enzymes in the human gastrointestinal system. These components raise the viscosity of the food matrix, limiting enzyme access to starch granules and delaying

**Table 1:** Comparative Nutritional and Phytochemical Profile of Black Wheat and Whole Wheat

| Parameters | Black Wheat | Whole Wheat | Reference |
|---|---|---|---|
| Protein (%) | 12.5–13.5 | 11.0–12.0 | *Garg et al., 2016; Li et al., 2018* |
| Dietary Fiber (%) | 12.0–13.0 | 10.0–11.0 | *Garg et al., 2016* |
| Carbohydrates (%) | 68.0–70.0 | 71.0–73.0 | *Li et al., 2018* |
| Total Anthocyanins (mg/100 g DW) | 120–160 | ND | *Garg et al., 2016; Liu et al., 2020* |
| Total Phenolics (mg GAE/100 g DW) | 230–270 | 110–130 | *Liu et al., 2020* |
| Antioxidant Activity (DPPH, µmol TE/100 g) | 750–820 | 300–360 | *Liu et al., 2020* |
| Antioxidant Activity (ABTS, µmol TE/100 g) | 900–960 | 400–450 | *Li et al., 2018* |
| Major Anthocyanins | Delphinidin- and Cyanidin- derivatives | None | *Garg et al., 2016* |

DPPH= 2,2-diphenyl-1-picrylhydrazyl; ABTS=2,2′-azinobis-(3-ethybenzothiazoline-6-sulfonic acid); GAE= Gallic Acid Equivalent.

carbohydrate breakdown, which leads to better glycaemic management and digestive function. On a whole-grain basis, black wheat contains around 1.15% total dietary fibre, the majority of which is insoluble fibre (Ariyarathna et al., 2025). Insoluble dietary fibre improves gastrointestinal health by increasing faecal volume and improving intestinal transit, lowering the risk of constipation. The inclusion of dietary fibre and bioactive substances in black wheat reflects the well-known advantages of whole grains, such as enhanced bowel function. Furthermore, fiber-induced changes in food matrix viscosity lower starch digestibility, resulting in improved carbohydrate digestion. These properties highlight black wheat's potential as a functional element for promoting digestive and metabolic health (Mohanty 2016).

### 2.3 Proteins

Protein quality is characterised by amino acid bioavailability, necessary amino acid composition, and ability to fulfil human metabolic requirements. Wheat proteins often have a low amino acid score (AAS = 43), suggesting a lack of critical amino acids (Jiang et al., 2008). In contrast, black wheat has been shown to have greater protein quality, with metabolomic tests detecting 96 amino acids and associated derivatives, as well as 17.7% higher protein content than normal wheat cultivars (Dhua et al., 2021). The main storage proteins in black wheat are glutenins and gliadins (prolamins), which influence dough functioning. Black wheat has a lower gluten index (~69.7) than normal wheat (98-99), however this value is within the ideal range for breadmaking, boosting its potential as a low-gluten raw material for specialised food items (Sharma et al., 2022). Anthocyanin-rich black wheat has total and essential amino acid concentrations of around 15.74% and 4.45%, respectively, and the amino acid profile stays constant after high-temperature drying. This heat stability promotes proper dough rheology and baking performance. Furthermore, lower in-vitro protein digestibility relative to conventional wheat suggests prolonged gastric retention and possible benefits for postprandial glycaemic regulation, emphasising the importance of further systematic evaluation of gluten properties and protein functionality in black wheat (Mak et al., 2006).

### 2.4 Minerals

Anthocyanin-rich black wheat types have a significantly increased mineral profile compared to regular wheat, which contributes to their higher nutritious value. Notably, the anthocyanin-rich black wheat variety BGW-76 has around four-fold higher calcium levels than the ordinary cultivar Jinchun-9, as well as a significantly higher phosphorus content (4.10 g/kg against 2.41 g/kg). These minerals are necessary for bone formation, skeletal maintenance, and cellular energy metabolism (Koksel et al., 2025). In addition to macrominerals, black wheat contains important trace elements including selenium, zinc, and iron (Fe). Selenium concentrations in black wheat (1.04 mg/kg) are much greater than those found in regular wheat (0.26 mg/kg), indicating that it has a role in immunological function, antioxidant defence, and inflammatory control (Saeed et al. 2025). Furthermore, pigmented wheat types regularly have higher zinc and iron levels than white wheat, providing a natural advantage for micronutrient biofortification and the prevention of mineral shortages (Sharma et al., 2018). Black wheat's higher mineral content is commonly linked to higher amounts of phenolic compounds and antioxidant activity, notably anthocyanins. This simultaneous enrichment of minerals and bioactive substances enhances black wheat's nutritional and functional value, implying possible health advantages due to its antioxidant capacity and anti-inflammatory properties (Pontieri Liu et al. 2022).

### 2.5 Vitamins

Black wheat is a rich source of critical vitamins. Niacin (vitamin $B_3$) is essential for energy metabolism, DNA synthesis, and skin integrity. Pantothenic acid (vitamin $B_5$) helps in haemoglobin formation, macronutrient metabolism, hormone synthesis, and cellular energy generation. Vitamin E (tocopherol) is a powerful antioxidant that protects erythrocytes from oxidative damage and promotes reproductive health. Analytical investigations found significant levels of vitamins $B_3$, $B_5$, and E in black wheat (Guo et al. 2013). Furthermore, the anthocyanin-rich black wheat variety BGW-76 has around 11.47 mg/kg of vitamin K, which represents a 1.6-fold increase over normal wheat. Metabolomic profiling has found up to 19 different vitamins in black wheat, highlighting its nutritional richness and potential as a functional food (Tekin et al., 2018).

## 3. Functional Compounds in Black Wheat

Wheat, in addition to macronutrients like carbs, proteins, and lipids, has a number of bioactive substances that contribute to its functional qualities. The principal types of useful chemicals include phenolic acids, flavonoids (including anthocyanins), and carotenoids, with black wheat having significantly greater quantities than other wheat kinds.

### 3.1 Phenolic Acids

Phenolic acids are physiologically active phytochemicals found in wheat in soluble (free or conjugated) and insoluble (bound) forms. They are generically classed as hydroxybenzoic acid derivatives (e.g., gallic, vanillic, syringic, and p-hydroxybenzoic acids) and hydroxycinnamic acid derivatives (e.g., ferulic, caffeic, p-coumaric, and sinapic acids). Bound phenolic acids are covalently bound to cell wall components (lignin, cellulose, hemicellulose, and pectin), rendering them less extractable than soluble equivalents; yet, both types have significant antioxidant action (Lan et al., 2024). Black wheat has a diverse range of phenolic acids, with ferulic acid being the most abundant. Phenolic acids are more concentrated in the bran fraction than in whole meal or refined flour, and black wheat has more of them than other wheat kinds. Studies have indicated that black wheat has a much larger soluble phenolic content than white wheat, as well as a higher total phenolic content in both free and bound forms. Metabolomic investigations have found over 50 phenylpropanoid chemicals in black wheat, which is dominated by hydroxycinnamic acids and has higher quantities of particular cinnamic acid derivatives than yellow and blue wheat cultivars (Zhang et al., 2018).

### 3.2 Flavonoids and Anthocyanins

Flavonoids are a broad family of polyphenolic chemicals with a C6-C3-C6 carbon skeleton that includes flavones, flavonols, flavanones, flavan-3-ols, isoflavones, chalcones, and anthocyanidins. Flavonoids are necessary for pigmentation, defence systems, and environmental interactions in plants (Li et al., 2015). Wheat grains contain numerous flavonoids (tricin, luteolin, quercetin, kaempferol, apigenin, naringenin, and vitexin), with tricin and its derivatives found mostly in the bran and hull fractions (Wang et al., 2020). Anthocyanins, a water-soluble flavonoid subclass, are the principal pigments that provide colouration in coloured wheat types. These chemicals are primarily formed from six anthocyanidins—cyanidin, delphinidin, malvidin, peonidin, petunidin, and pelargonidin—and differ in glycosylation and acylation patterns, which dictate pigment intensity and colour. Anthocyanins dominate the flavonoid profile in black wheat and concentrate in the outer grain layers, giving the crop its distinct dark colouration (Feng et al., 2022). Quantitative and metabolomic investigations have repeatedly demonstrated that black wheat contains considerably more total flavonoids than purple, blue, yellow, and regular wheat in both whole grains and refined flour. Black wheat contains up to 174 distinct flavonoids, demonstrating its biochemical diversity. This enrichment is supported by increased expression of critical structural genes involved in flavonoid and anthocyanin biosynthesis, including as TaCHI, TaANS, TaF3H, TaUGT, TaDFR, and TaMT, which all contribute to increased pigment production and accumulation (Sun et al., 2024).

### 3.3 Antioxidant Activity

Antioxidant activity in wheat varies greatly amongst coloured types, with black wheat usually having the greatest activity. Comparative investigations using total phenolic content and radical scavenging tests revealed a clear antioxidant capacity hierarchy (black > purple > blue

**Table 2:** Functional properties of black wheat, underlying biological mechanisms, key experimental findings, and potential food and nutraceutical applications.

| Functional Property | Biological Mechanism | Key Experimental Finding | Potential Application | Reference |
|---|---|---|---|---|
| Antioxidant capacity (DPPH) | Free-radical scavenging by anthocyanins and phenolics | Black wheat extracts showed DPPH scavenging activity up to ~78% | Natural antioxidant ingredient | *Sharma et al., 2018* |
| Antioxidant capacity (ABTS) | Electron and hydrogen donation by polyphenols | Significant ABTS radical inhibition observed in black wheat extracts | Antioxidant formulations | *Sharma et al., 2018* |
| PCL / ORAC activity | Scavenging of peroxyl radicals | High PCL/ORAC values indicating strong antioxidant potential | Antioxidant capacity index for food formulations | *Sharma et al., 2018* |
| Total anthocyanin content (TAC) | Accumulation of cyanidin- and delphinidin-based pigments in bran layers | High TAC levels reported in black wheat grains | Natural food colorants and nutraceuticals | *Wang et al., 2023* |
| Total phenolic content (TPC) | Presence of bound and free phenolic acids | Significantly higher TPC compared with white wheat | Antioxidant-rich food ingredients | *Kumari et al., 2020* |
| Anti-inflammatory activity | Suppression of pro-inflammatory signaling pathways | Reduced TNF-α and IL-6 levels in diet-induced inflammation models | Anti-inflammatory nutraceuticals | *Sharma et al., 2018* |
| ROS inhibition | Reduction of oxidative stress and ROS generation | Black wheat extracts lowered intracellular ROS levels | Mitigation of oxidative stress–related disorders | *Sharma et al., 2018* |
| Antimicrobial activity | Cell membrane disruption and oxidative damage in microbes | Inhibition of common foodborne pathogens | Natural food preservation agents | *Sharma et al., 2020* |
| Processing stability (baking & fermentation) | Partial retention of phenolics and anthocyanins after processing | Chapatti retained higher phenolics; fermented products showed reduced but stable anthocyanins | Colored functional bakery and beverage products | *Kumari et al., 2020; Singh et al., 2023* |
| Metabolite and nutrient enrichment | Enhanced accumulation of glutathione, lipids, and minerals | Elevated glutathione and mineral levels in black wheat | Functional whole-grain foods | *Wang et al., 2023; Dhua et al., 2021* |
| Nutrigenomic and metabolic modulation | Anthocyanin-mediated regulation of metabolic and antioxidant genes | Upregulation of genes linked to antioxidant defense | Basis for precision nutrition applications | *Sharma et al., 2020* |

DPPH= 2,2-diphenyl-1-picrylhydrazyl; ABTS=2,2′-azinobis-(3-ethybenzothiazoline-6-sulfonic acid); PCL= Photochemiluminescence ; ORAC= Oxygen Radical Absorbance Capacity

> yellow wheat) (Siebenhandl et al., 2007). Black wheat has enhanced antioxidant activity due to its high phenolic acid and anthocyanin contents. Black wheat, in particular, has more delphinidin-3-glucoside, an anthocyanin with greater antioxidant properties than cyanidin- and pelargonidin-based anthocyanins found in purple and blue wheat cultivars (Sharma et al., 2023). Radical scavenging experiments, including DPPH inhibition tests, consistently show that anthocyanin-rich black wheat genotypes have much better antioxidant activity than other coloured wheat genotypes (Yi 2014). Although specific bran fractions of blue or purple wheat may have higher bound phenolic content, this localised impact does not outweigh black wheat's total antioxidant capacity when measured at the whole grain or flour level (Ed Nignpense et al., 2022). These findings demonstrate that black wheat has a significant antioxidant advantage over other wheat kinds due to its higher quantities and unique composition of anthocyanins and phenolic compounds (Krawęcka et al., 2022).

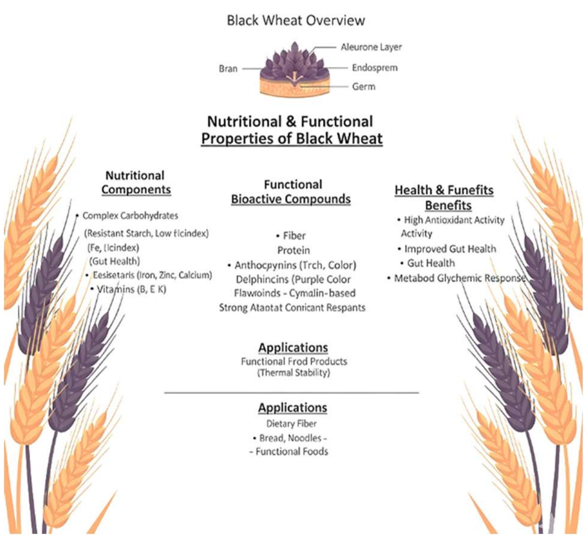


**Fig. 1:** Mechanistic role of anthocyanins in black wheat showing their antioxidant action and linkage to metabolic and gut health benefits.

## 4. Recent Development in Black Wheat Food Products

Black wheat offers a significant improvement in cereal biofortification, providing a nutritionally rich alternative to regular wheat by combining excellent macronutrient quality with a strong bioactive chemical profile. This type, developed by standard hybridisation, is distinguished by its rich colouration, which is due to a 20 to 30 time's greater anthocyanin deposition in the bran and aleurone layers than in regular white wheat. Its nutritional profile is distinguished by high protein quality, balanced amino acids, enhanced dietary fibre, and elevated quantities of important minerals (iron, zinc, and selenium). Functionally, black wheat has a high antioxidant capacity (DPPH inhibition of 70-80%) and a lower glycaemic index (GI 45-50), which help with metabolic management, anti-inflammatory effects, and gut health. These properties, combined with its high thermal stability during processing, have enabled its successful incorporation into a wide range of functional food applications (bread, chapatti, noodles, fermented products, etc.), effectively bridging the gap between traditional diets and modern health requirements (Abdullah et al., 2024).

### 4.1 Development Through CRISPR-Cas9 Technology.

CRISPR/Cas9 genome editing is a powerful method for improving black wheat's nutritional composition, anthocyanin content, and functional food attributes. Black wheat is an important functional food with health advantages due to its high anthocyanin content, which contributes to its black colouration and strong antioxidant activity. However, because wheat has a big, hexaploid genome, typical breeding methods cannot increase complicated features such as micronutrient density and anthocyanin production. CRISPR technology accelerates the production of black wheat varieties with superior biofortification features by allowing for precise editing of key genes involved in nutrient absorption, storage, and secondary metabolite pathways (Nasim et al., 2025). One possible use of CRISPR in black wheat biofortification is the reduction of phytic acid, an antinutrient that binds to key elements like iron and zinc, lowering their bioavailability. Using CRISPR/Cas9, the TaIPK1 gene, which codes for an enzyme required for phytic acid production, was effectively disrupted in wheat, resulting in a significant drop in phytic acid levels and a rise in bioavailable iron and zinc accumulation in grains (Khan et al., 2024). Using this method, black wheat's nutritional profile might be enhanced, addressing malnutrition and hidden hunger in communities that rely on wheat as a staple. Additionally, by focussing on regulatory genes in the flavonoid pathway, CRISPR can be utilised to increase anthocyanin production, potentially increasing antioxidant content and functional food value (Saha et al., 2025). CRISPR-mediated editing can improve the nutritional value of black wheat by changing genes involved in various metabolic pathways, such as protein quality, starch composition, and vitamin content, in addition to micronutrients and antioxidants. Monisha et al. (2025) suggest that altering genes that affect gluten composition or starch production can broaden the functional food uses of black wheat. CRISPR's accuracy and multiplexing capabilities allow for the simultaneous change of numerous features, accelerating the production of black wheat types with significant nutritional improvements. The combination of CRISPR with cutting-edge breeding approaches like as speed breeding and multi-omics analysis has expedited black wheat development. While multi-omics approaches aid in the identification of potential genes and metabolic networks for focused editing, speed breeding shortens generation durations and allows for the rapid fixing of changed phenotypes (Zulfiqar et al., 2024). These strategies work together to promote sustainable agriculture and food security by making it simpler to create nutrient-dense, climate-resilient black wheat cultivars that can thrive in a range of conditions. Despite its potential, employing CRISPR in black wheat presents obstacles. These include regulatory concerns, public acceptability, and the challenge of editing a polyploid genome with numerous gene copies. Off-target effects and the effective distribution of CRISPR components into wheat cells require further development (Shoeb et al., 2024). However, continuous developments in CRISPR technology, such as base and prime editing, as well as improved transformation approaches, are addressing these constraints. This advancement makes genome editing a realistic approach to enhancing black wheat. Finally, CRISPR/Cas9 genome editing has great potential for upgrading black wheat as a biofortified cereal by increasing its vitamin content, anthocyanin levels, and functional food qualities (Ibrahim et al., 2025). Targeted disruption of antinutrient genes such as TaIPK1 and augmentation of flavonoid biosynthesis pathways can improve the nutritional and health advantages of black wheat. CRISPR, when combined with contemporary breeding technology, has the potential to hasten the production of superior black wheat types that will help battle starvation and promote human health throughout the world. Continued research and collaboration among scientists, breeders, and policymakers will be required to realise CRISPR's full promise in black wheat biofortification and functional food applications (Bairwa et al., 2025).

**Table 3:** Target genes and metabolic pathways underlying genome-edited nutritional and functional trait enhancement.

| Target gene | Pathway / Function | Edited trait | Nutritional / functional outcome | Reference |
|---|---|---|---|---|
| *TaIPK1* | Phytic acid biosynthesis | Reduced phytic acid | Increased bioavailable Fe and Zn | *Zia et al., 2025* |
| Flavonoid regulatory genes (e.g., MYB, bHLH) | Anthocyanin biosynthesis | Enhanced anthocyanin accumulation | Improved antioxidant activity | *Sharma et al., 2024* |
| Nutrient transporter genes | Mineral uptake and storage | Improved micronutrient loading | Enhanced grain mineral density | *Nasim et al., 2025* |
| Gluten-related genes | Protein composition | Modified gluten quality | Expanded functional food applications | *Kaur et al., 2024* |
| Starch biosynthesis genes | Carbohydrate metabolism | Altered starch composition | Improved nutritional and processing quality | *Zhang et al., 2025* |

## 5. Conclusion

Black wheat represents a significant advancement in cereal biofortification, combining superior nutritional quality with high levels of bioactive compounds. Its elevated anthocyanin content, balanced protein profile, dietary fiber, and essential minerals make it a functional cereal capable of addressing micronutrient deficiencies and promoting overall health. The cereal's strong antioxidant activity, low glycemic index, and thermal stability during processing highlight its potential for diverse functional food applications, contributing to metabolic regulation, gut health, and anti-inflammatory effects.

## 6. Feature outlook

Future research should focus on optimizing agronomic practices and breeding strategies to enhance yield while maintaining high bioactive content. The application of genomics and metabolomics can help identify the genetic factors underlying anthocyanin accumulation and nutrient bioavailability, enabling targeted improvements. Additionally, long-term clinical studies are necessary to validate the health benefits of black wheat consumption. Expanding product development and consumer acceptance studies will be crucial for the successful commercialization of black wheat-based functional foods, providing sustainable dietary solutions to improve public health.

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