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Unlocking the Health Potential of Foxtail Millet: Phytopharmacology, Bioactive Compounds and Therapeutic Applications: A Review

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ABSTRACT

Foxtail millet, a nutrient-dense and drought-resistant cereal, has gained recognition for its exceptional nutritional and therapeutic properties. This review comprehensively examines its bioactive compounds, including polyphenols, flavonoids, dietary fibers, essential amino acids and unsaturated fatty acids, which contribute to its antioxidant, anti-inflammatory, hypoglycemic and hypolipidemic effects. Advanced analytical techniques such as HPLC-MS, GC-MS and NMR spectroscopy have enabled precise characterization of these phytochemicals, enhancing our understanding of their health benefits. The grain's low glycemic index and gluten-free nature make it ideal for diabetes management and celiac patients. Additionally, its cardioprotective effects, mediated through cholesterol reduction and blood pressure regulation, highlight its potential in preventing cardiovascular diseases. The prebiotic fiber and resistant starch in foxtail millet promote gut health by modulating beneficial microbiota and producing short-chain fatty acids. Despite its benefits, challenges such as antinutritional factors and bioavailability limitations persist. Processing techniques like fermentation can mitigate these issues. Future research should focus on optimizing extraction methods, clinical validation of health benefits and developing fortified food products. With its rich phytopharmacological profile and sustainable cultivation, foxtail millet emerges as a promising functional food for addressing global nutritional security and metabolic health challenges.

Key words: Analytical chemistry, Bioactive compounds, Foxtail millet, Nutritional properties, Phytopharmacology.

Foxtail millet (*Setaria italica*), a drought-resistant cereal crop, has garnered significant attention due to its exceptional nutritional profile and health-promoting properties (Harish *et al.,* 2024). As a staple food in many Asian and African countries, it is rich in carbohydrates (60-70%), proteins (10-12%) and dietary fiber (6-8%), making it a valuable source of sustained energy (Kalsi and Bhasin, 2023). Unlike major cereals such as wheat and rice, foxtail millet has a low glycemic index (GI ≈ 50), which is beneficial for managing diabetes and metabolic disorders (Usman *et al.,* 2022; Sahana and Vijayalaxmi, 2024). Additionally, it contains essential amino acids, including leucine, isoleucine and methionine, though lysine remains a limiting factor (Sivakumar *et al.,* 2022; Mazzola *et al.,* 2024). Its gluten-free nature further enhances its suitability for celiac patients, positioning it as a functional food in modern diets (Sudha *et al.,* 2022).

Beyond macronutrients, foxtail millet is a reservoir of bioactive compounds, including phenolic acids, flavonoids and lignans, which contribute to its antioxidant and anti-inflammatory properties (Sasi *et al.,* 2023). Studies indicate that ferulic acid, *p*-coumaric acid and quercetin derivatives are predominant phenolics, with total phenolic content ranging from 120-250 mg GAE/100 g (Bento *et al.,* 2017). These compounds exhibit free radical scavenging activity, reducing oxidative stress markers *in vitro* and *in vivo* (Frond *et al.,* 2019). Furthermore, foxtail millet contains phytosterols (β-sitosterol and campesterol) and gamma-aminobutyric acid (GABA), which are associated with cholesterol-lowering and neuroprotective effects, respectively (Kumari *et al.,* 2025). The synergistic action of these phytochemicals justifies its potential in preventing chronic diseases, including cardiovascular disorders and cancer (Adetuyi *et al.,* 2025).

Foxtail millet is an excellent source of essential micronutrients, particularly iron (2.8-5.5 mg/100 g), zinc

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(1.7-3.5 mg/100 g) and calcium (20-45 mg/100 g), crucial for addressing micronutrient deficiencies in developing regions (Ingle *et al.,* 2023). However, the presence of antinutritional factors such as phytic acid (0.4-1.2%) can impair mineral bioavailability. Recent processing techniques like fermentation, germination and decortication have been shown to reduce phytic acid by 30-60%, enhancing iron and zinc absorption (Bandyopadhyay *et al.,* 2017). Additionally, foxtail millet contains B-complex vitamins, notably niacin (1.5-3.0 mg/100 g) and folate (25-45 μg/100 g), supporting metabolic and neurological functions (Gao *et al.,* 2024). These attributes highlight its role in combating hidden hunger and improving public health outcomes (Adetuyi *et al.,* 2025).

Despite its nutritional richness and traditional uses, there is limited systematic exploration of its mechanisms of action, bioavailability and clinical efficacy in managing chronic diseases such as diabetes, cardiovascular disorders and inflammation (Sasi *et al.,* 2023). This review addresses a critical research gap by consolidating scattered studies on foxtail millet's bioactive compounds, pharmacological properties and therapeutic potential, which have not been comprehensively analyzed in existing literature. This review is significant as it synthesizes current knowledge, highlights understudied bioactive components and identifies future research directions to validate its health benefits.

Phytochemical composition of foxtail millet

Recent advancements in analytical techniques, including HPLC-MS, GC-MS and NMR spectroscopy, have enabled precise quantification of foxtail millet's nutraceutical components (Pujari and Hoskeri, 2022). Metabolomic studies reveal dynamic changes in its phytochemical profile under varying agronomic conditions, suggesting opportunities for biofortification (Suma and Urooj, 2012). Furthermore, genomic and proteomic approaches are identifying key genes responsible for nutrient synthesis, paving the way for genetically enhanced varieties (Sharma and Niranjan, 2018). As global interest shifts toward sustainable and nutrient-dense crops, foxtail millet stands out as a promising candidate for functional food development, warranting further research into its nutraceutical applications and health benefits (Kuruburu *et al.,* 2022).

Macronutrient profile

Foxtail millet is a nutritionally dense grain with a balanced macronutrient composition (Bandyopadhyay *et al.,* 2017). It is primarily composed of slow-digesting starches, which contribute to a low glycemic index (GI), making it beneficial for glycemic control and diabetes management (Kola *et al.,* 2020). The high fiber content further aids in prolonged satiety and improved digestive health (Arya and Bisht, 2022). It contains approximately 60-70% carbohydrates, predominantly in the form of complex starches and dietary fiber, which contribute to its low glycemic index (GI) and slow digestion, making it beneficial for blood sugar management (Abedin *et al.,* 2022). The grain also provides 10-12% protein, containing essential amino acids such as lysine (3.2-4.6 g/100 g), methionine (1.7-2.3 g/100 g) and leucine (7.4-9.8 g/100 g), which are often limited in other cereals (Arora *et al.,* 2023). This makes foxtail millet a valuable protein source, particularly in plant-based diets. Foxtail millet contains essential amino acids, including lysine, methionine and leucine, which are often limited in other cereal grains (Xing *et al.,* 2023). This makes it a valuable protein source, particularly in vegetarian diets. The lipid content in foxtail millet is relatively low but includes a favorable ratio of omega-3 to omega-6 fatty acids, which may support cardiovascular health (Madhavilatha *et al.,* 2022; Ingle *et al.,* 2023) Additionally, foxtail millet has a relatively low fat content (2-4%), with a favorable fatty acid profile, including a balanced ratio of omega-3 to omega-6 fatty acids (Nadeem *et al.,* 2020). The lipid fraction consists of unsaturated fats, primarily linoleic acid (omega-6) and a-linolenic acid (omega-3), which support cardiovascular health (Bandyopadhyay *et al.,* 2017; Umamaheswari *et al.,* 2021). The high fiber content (6-12%) further enhances its nutritional benefits by promoting digestive health (Abedin *et al.,* 2022).

Micronutrient profile

Foxtail millet is a nutritionally dense grain, particularly rich in B-complex vitamins and essential minerals. It contains significant amounts of thiamine (B1) (0.59 mg/100 g), riboflavin (B2) (0.11 mg/100 g), niacin (B3) (3.2 mg/100 g) and pyridoxine (B6) (0.38 mg/100 g), which are crucial for energy metabolism and neurological function (Bandyopadhyay *et al.,* 2017). Additionally, foxtail millet provides vitamin E (0.5 mg/100 g), an antioxidant that supports skin health and immune function. These vitamins contribute to the grain's potential in combating micronutrient deficiencies, particularly in regions where it is a dietary staple (Xing *et al.,* 2023). The mineral profile of foxtail millet is equally impressive, with high levels of iron (6.3 mg/100 g), calcium (31 mg/100 g), magnesium (81 mg/100 g), phosphorus (290 mg/100 g) and zinc (2.4 mg/100 g) (Abedin *et al.,* 2022).

Bioactive compounds

Foxtail millet is a rich source of bioactive compounds, including polyphenols, flavonoids and tannins, which contribute to its antioxidant and anti-inflammatory properties (Kuruburu *et al.,* 2022). Studies indicate that foxtail millet contains approximately 98.5 mg/100 g of total polyphenols, with flavonoids such as quercetin and kaempferol present in significant amounts (Hutabarat and Bowie, 2022). These compounds help to neutralize free radicals, reducing oxidative stress and inflammation, which are linked to chronic diseases like diabetes and cancer (Dey *et al.,* 2022). Additionally, tannins (about 0.3-0.6% of dry weight) in foxtail millet exhibit antimicrobial and anti-inflammatory effects, further enhancing its functional food potential (Sharma and Sharma, 2022). The presence of these bioactive molecules makes foxtail millet a promising dietary component for disease prevention (Mikulajova *et al.,* 2017). Moreover, foxtail millet contains lignans (*e.g.*, secoisolariciresinol) and saponins, which offer cardioprotective and immunomodulatory benefits (Wang *et al.,* 2023). Lignans, present at 0.5-2.0 mg/ 100 g, have been associated with reduced risk of cardio-vascular diseases due to their cholesterol-lowering and anti-atherogenic effects (Chethan Kumar *et al.,* 2022). Saponins, found in concentrations of 0.1-0.3%, enhance immune function by modulating cytokine production and exhibit hypocholesterolemic activity (Sharma *et al.,* 2015).

Phytopharmacological properties

Antioxidant activity

Foxtail millet exhibits significant antioxidant activity, primarily attributed to its high phenolic and flavonoid content (Sharma *et al.,* 2015). Studies have shown that foxtail millet contains total phenolic content ranging from 168.2 to 328.5 mg GAE/ 100 g and total flavonoid content between 25.4 and 58.6 mg QE/100 g, depending on the variety and processing methods (Suma and Urooj, 2012). These bioactive compounds contribute to its free radical scavenging ability, as demonstrated by its high DPPH (1,1-diphenyl-2-picrylhydrazyl) radical inhibition (IC50 values of 1.2-2.8 mg/ mL) and ABTS (2,2'-azino-bis(3-ethylbenzothiazoline-6-sulfonic acid)) radical scavenging activity (IC50 values of 0.9-2.1 mg/mL) (Sharma *et al.,* 2015). The presence of phenolic acids such as ferulic, *p*-coumaric and syringic acids further enhances its antioxidant potential, making it effective in neutralizing reactive oxygen species (ROS) (Zhang *et al.,* 2017). Research indicates that regular consumption of foxtail millet can reduce lipid peroxidation measured by malondialdehyde (MDA) levels by 20-35% in animal models (Sharma *et al.,* 2018). Additionally, its flavonoids, *i.e.*, apigenin and luteolin, modulate antioxidant enzymes like superoxide dismutase (SOD) and glutathione peroxidase (GPx), improving cellular defense (Xu *et al.,* 2025).

Antidiabetic and glycemic control

Foxtail millet has demonstrated significant potential in managing diabetes and improving glycemic control due to its slow carbohydrate digestion (Xu *et al.,* 2025). The grain's high dietary fiber content (6.7-8.0%) and resistant starch (1.2-2.5%) contribute to a low glycemic index (GI ≈ 50-58), which helps in gradual glucose release and prevents postprandial blood sugar spikes (Makwana *et al.,* 2025). A study found that foxtail millet-based diets significantly reduced fasting blood glucose levels (by ~15-20%) in diabetic rats compared to control groups, highlighting its role in stabilizing blood sugar levels (Goel *et al.,* 2025). Additionally, its polyphenols and flavonoids (*e.g.*, quercetin and ferulic acid) inhibit carbohydrate- digesting enzymes like α-amylase and α-glucosidase (Candra *et al.,* 2025). Foxtail mill*et al*so enhances insulin sensitivity through its bioactive compounds, such as magnesium (~130 mg/100 g) and phytochemicals like vitexin and orientin (Khan *et al.,* 2025). Research reported that foxtail millet consumption improved insulin sensitivity (HOMA-IR reduction by ~18%) in type 2 diabetic patients, attributed to its antioxidant and anti-inflammatory properties (Xu *et al.,* 2025).

Cardioprotective effects

Foxtail millet has demonstrated significant cardioprotective effects, primarily by reducing low-density lipoprotein (LDL) cholesterol and promoting overall heart health (Goel *et al.,* 2025). A study found that the soluble dietary fiber and polyphenols in foxtail millet effectively lower LDL cholesterol levels by inhibiting cholesterol absorption in the gut and enhancing its excretion (Candra *et al.,* 2025). Additionally, the grain's high fiber content aids in improving lipid metabolism, reducing the risk of atherosclerosis and coronary heart disease (Makwana *et al.,* 2025). The presence of essential fatty acids, such as linoleic acid, further contributes to its cholesterol-lowering properties, making foxtail millet a valuable dietary component for cardiovascular disease prevention (Zhang *et al.,* 2017). Magnesium acts as a natural calcium channel blocker, promoting vasodilation and reducing vascular resistance, which helps maintain healthy blood pressure levels (Sharma *et al.,* 2015). The fiber content also aids in managing hypertension by improving endothelial function and reducing oxidative stress. A study highlighted that regular consumption of foxtail millet significantly decreased systolic and diastolic blood pressure in hypertensive individuals (Abedin *et al.,* 2022).

Gut health and prebiotic potential

Foxtail millet exhibits notable benefits for gut health due to its high dietary fiber content, which acts as a prebiotic to support beneficial gut microbiota (Li *et al.,* 2025). A study found that the insoluble fiber in foxtail millet (approximately 8-12% of its composition) enhances microbial diversity in the colon, promoting the growth of *Bifidobacteria* and *Lactobacillus* species (Chakraborty *et al.,* 2025). These microbes play a crucial role in maintaining intestinal barrier function and reducing inflammation, thereby improving digestive health (Manju *et al.,* 2025). Additionally, the fermentation of foxtail millet's fiber produces short-chain fatty acids (SCFAs), such as acetate, propionate and butyrate, which provide energy to colonocytes and help prevent gut-related disorders like irritable bowel syndrome (IBS) and colorectal cancer (Sandhya *et al.,* 2025). Another key component of foxtail millet is resistant starch (RS), which accounts for about 3-5% of its total starch content. Resistant starch resists digestion in the small intestine and undergoes fermentation in the colon, where it enhances gut motility and promotes the production of beneficial metabolites (Rayasam *et al.,* 2025). Research demonstrated that foxtail millet's resistant starch significantly increases fecal bulk and reduces intestinal transit time, alle*via*ting constipation (Vila-Real *et al.,* 2025).

Analytical techniques in foxtail millet research

Foxtail millet research employs various analytical techniques to study its nutritional, genetic and agronomic traits (Wang *et al.,* 2025). Proximate composition analysis, including protein, fat, fiber and carbohydrate quantification, is conducted using methods like Kjeldahl, Soxhlet extraction and Van Soest procedures (Khan *et al.,* 2025). Molecular techniques such as SSR markers, SNP genotyping and next-generation sequencing (NGS) facilitate genetic diversity and breeding studies (Wang *et al.,* 2025). Advanced tools like high-performance liquid chromatography (HPLC) and gas chromatography-mass spectrometry (GC-MS) are used for phytochemical profiling, while Fourier-transform infrared spectroscopy (FTIR) and near-infrared spectroscopy (NIRS) aid in rapid quality assessment (Yue *et al.,* 2025).

Chromatographic techniques

Chromatographic techniques have been effectively utilized to analyze the bioactive compounds in foxtail millet (Khan *et al.,* 2025). HPLC is widely employed for polyphenol profiling due to its high resolution and sensitivity (Wang *et al.,* 2025). Additionally, GC-MS is used for analyzing lipids and volatile compounds, providing insights into the fatty acid composition and aroma profiles of foxtail millet (Yue *et al.,* 2025). GC-MS is particularly valuable for detecting volatile organic compounds and lipid derivatives, contributing to the assessment of its culinary and storage properties (Rayasam *et al.,* 2025). HPLC-based polyphenol profiling helps in evaluating its antioxidant potential, while GC-MS facilitates the characterization of lipid metabolism and flavor components (Manju *et al.,* 2025). These techniques collectively support the valorization of foxtail millet as a functional food (Yue *et al.,* 2025). Moreover, Table 1 summarizes the case studies on chromatographic techniques applied in foxtail millet.

Spectroscopic methods

Foxtail millet is a nutritionally rich cereal grain known for its high phenolic and flavonoid content, which contribute to its antioxidant, anti-inflammatory and health-promoting properties (Manju *et al.,* 2025). Spectroscopic techniques such as UV-Visible (UV-Vis) spectroscopy and Fourier Transform Infrared (FTIR) spectroscopy are widely used for the quantification and characterization of these bioactive compounds (Yue *et al.,* 2025). These methods provide rapid, non-destructive and accurate analysis of foxtail millet's phytochemical composition, aiding in food quality assessment and nutraceutical development (Manju *et al.,* 2025). UV-Vis spectroscopy is a fundamental analytical technique used to quantify phenolic and flavonoid content in foxtail millet (Goel *et al.,* 2025). Phenolic compounds exhibit strong absorption in the 280-320 nm range due to aromatic $\pi \rightarrow \pi$ transitions, while flavonoids show characteristic peaks at 360-380 nm due to conjugated systems (Goel *et al.,* 2025). The Folin-ciocalteu (FC) assay is commonly used for total phenolic content (TPC)

Table 1: Chromatographic techniques in foxtail millet analysis.

Parameters	Findings	Method used	Reference
Phytochemical screening	Nutrient-dense grains with bioactive compounds	GC-MS	Trivedi and Gupta (2023)
Flavour volatiles	Hybrid foxtail millet had different volatile profiles compared to conventional varieties	GC-IMS	Yue *et al.* (2025)
Flavor volatiles	55 volatile components identified; differences among black, green, white and yellow foxtail millet	GC-IMS	Jin *et al.* (2023)
Polysaccharide structure and bioactivity	Antioxidant and immunostimulatory activities confirmed	GC-MS, SEC, HPLC	Zhang *et al.* (2025)
Metabolite differences	Regional variations in nutritional composition detected	UPLC-Q-Orbitrap HRMS	Yang *et al.* (2021)
Kaempferol content and antidiabetic effects	Foxtail millet exhibited antidiabetic properties; Kaempferol verified	HPTLC	Singh *et al.* (2022)
Antioxidant and anticancer activity	Reduced breast cancer cell viability: high antioxidant activity	LC-QTOF-MS	Kuruburu *et al.* (2022)
Odor profile	Spring and summer sowing influenced volatile compounds	GC-MS	Li *et al.* (2025)
Rheological and nutritional properties	Viscosity and loss modulus varied: rich in polyphenols	HPLC, Rheometry	Kalsi and Bhasin (2023)
Storage stability under light conditions	Red light exposure helped maintain quality during storage	Spectrophotometry	Liang *et al.* (2021)

GC-MS- Gas chromatography-Mass spectrometry; GC-IMS- Gas chromatography-Ion mobility spectrometry; SEC- Size-exclusion chromatography; HPLC- High-performance liquid chromatography; UPLC-Q-Orbitrap HRMS- Ultra-performance liquid chromatography-Quadrupole-orbitrap high-resolution mass spectrometry; HPTLC- High-performance thin-layer chromatography; LC-QTOF-MS- Liquid chromatography-quadrupole time-of-flight mass spectrometry; HPLC- High-performance liquid chromatography.

determination, whereas the aluminum chloride (AlClƒ) colorimetric method is applied for flavonoid quantification (Wang *et al.,* 2025). However, Table 2 summarizes the case studies on UV-Vis Spectroscopy for foxtail millet analysis. Moreover, FTIR spectroscopy is used to identify functional groups in foxtail millet, such as O-H (3300 cm^{-1}, phenolics), C=O (1740 cm^{-1}, esters) and C=C (1600 cm^{-1}, aromatic rings) (Wang *et al.,* 2025). This technique helps in understanding structural changes due to processing and interactions between biomolecules (Makwana *et al.,* 2025). Table 3 summarizes the case studies on FTIR Spectroscopy for foxtail millet analysis.

Omics technologies

Recent advances in omics technologies have enabled comprehensive biochemical profiling of foxtail millet (Zhang *et al.,* 2025). Metabolomic studies using LC-MS and GC-MS have identified key bioactive compounds in foxtail millet, including phenolic acids, flavonoids and GABA, with germination and fermentation shown to significantly

Table 2: UV-Vis spectroscopy for foxtail millet analysis.

Study	Key findings	Reference
Impact of UV radiation and thermal treatment on foxtail millet flour	Particle size changes observed; Absorbance measured at 500 nm (UV-Vis)	Harshitha *et al.* (2024)
Characterization of phenolics in colored foxtail millets	Phenolic content varied by millet color; Bioaccessibility of phenolics assessed	Gao *et al.* (2024)
Structural and bioactivity study of foxtail millet polysaccharides	FM-D1 polysaccharide structure analysed; Antioxidant and immunostimulatory effects observed	Zhang *et al.* (2025)
Hyperspectral estimation of protein in foxtail millet	Canopy spectral reflectance used for protein prediction; Anthrone method for carbohydrate analysis	Li *et al.* (2024)
Nutritional and aroma profiling of colored foxtail millet	Mineral and aroma compound variations detected	Li *et al.* (2021)
HIU-induced functionalization of foxtail millet protein	Improved solubility and emulsification; Structural modifications observed	Sharma *et al.* (2023)
Germination effects on foxtail millet flour	Reduction in saponins, tannins, phytic acid; Increased phenolic content	Kumari *et al.* (2023)
Methylene blue removal by foxtail millet shell	Effective biosorbent for dyes and heavy metals; Reusability demonstrated	He *et al.* (2022)
Cold plasma treatment on foxtail millet storage stability	Reduced microbial load; Improved shelf life	Wang *et al.* (2022)
Cold plasma-assisted germination of foxtail millet	Faster germination; Enhanced nutrient composition	Monica *et al.* (2023)

Table 3: FTIR spectroscopy for foxtail millet analysis.

Parameter analyzed	Findings	References
Molecular interactome and starch-Protein matrix	Ozonation altered secondary protein structures in foxtail millet flour, as evidenced by FTIR spectra.	Sharma *et al.,* 2022
Functional properties	Biological processing (*e.g.*, fermentation) improved techno-functional characteristics (*e.g.*, solubility, water absorption).	Sharma and Sharma, 2022
Phytochemical constituents	Fermentation increased bioactive compounds (phenolics, flavonoids) and reduced anti-nutrients.	Sharma and Sharma, 2022
Antioxidant activity	Ozonation and fermentation enhanced free radical scavenging activity due to increased polyphenols.	Sharma *et al.,* 2022
FTIR Spectral Analysis	FTIR revealed changes in protein secondary structures (α-helix, β-sheet) and starch crystallinity after processing.	Sharma *et al.,* 2022; Lv *et al.,* 2023
Structural alterations	Accelerated storage induced protein aggregation and starch retrogradation in foxtail millet porridge.	Lv *et al.,* 2023
Particle size effects	Mechanical grinding of bran altered functional groups (FTIR) and improved solubility.	Liang *et al.,* 2022
Thermal stability	Foxtail millet husk composites with PLA/PBAT showed reduced thermal degradation.	Babu *et al.,* 2024
Immunostimulatory activity	Polysaccharides from foxtail millet exhibited antioxidant and immune-enhancing effects.	Zhang *et al.,* 2025

enhance these metabolites (Ingle *et al.,* 2023). Proteomic analyses through 2D-Gel electrophoresis and LC-MS/MS have characterized numerous storage and stress-responsive proteins that influence nutritional quality and abiotic stress resistance (Muruganantham *et al.,* 2025). Nutrigenomic investigations have revealed how millet-derived compounds interact with human metabolism, demonstrating anti-diabetic effects through modulation of PPAR-γ and GLUT4 gene expression, anti-inflammatory activity *via* NF-κB pathway inhibition and gut microbiome modulation by increasing beneficial bacteria like *Bifidobacterium* and *Lactobacillus* (Zhang *et al.,* 2025). Clinical and animal studies have further shown that foxtail millet consumption can positively regulate lipid metabolism genes and reduce obesity-related gene expression (Meena *et al.,* 2024).

Moreover, the following studies highlights advancements in milletomics, focusing on integrated omics approaches to understand genetic progression and nutritional improvement in millets, particularly foxtail millet Zhang *et al.* (2025); Mazumder *et al.* (2024) employed metabolomics-centered multi-omics to identify stress-responsive proteins and metabolic pathways in foxtail millet cultivars, revealing key molecular mechanisms under stress conditions. Meena *et al.* (2024) emphasized omics-aided crop improvement, noting limited but growing proteomics applications in foxtail millet, while Sasi *et al.* (2023) explored nutraceutical potential through metabolomic and genomic insights. Shingote *et al.* (2023) reviewed omics tools like proteomics and metabolomics for millet nutritional enhancement and Rahim *et al.* (2023) advocated pan-omics integration for underutilized cereals. Rajendrakumar (2022) identified gaps in proteomic and metabolomic studies in small millets under climate change, while Kumar *et al.* (2021) discussed genomics-assisted quality improvement. Singh *et al.* (2022) highlighted abiotic stress tolerance in finger millet using omics and Yadav *et al.* (2023) and Joshi *et al.* (2021) justified nutrigenomics' role in leveraging high-throughput omics for cereal biofortification and nutritional studies. Collectively, these studies demonstrate the potential of integrated omics genomics, transcriptomics, proteomics and metabolomics to enhance millet resilience, nutritional value and climate adaptability (Zhang *et al.,* 2025).

Challenges and future directions

Foxtail millet is a nutrient-rich cereal with potential nutraceutical benefits, but optimizing its extraction and bioavailability poses significant challenges (Zhang *et al.,* 2025). The grain's hard seed coat and complex starch-protein matrix hinder efficient nutrient extraction, requiring advanced processing techniques such as enzymatic hydrolysis, fermentation, or milling to enhance bioaccessibility (Sachdev *et al.,* 2021). Additionally, the bioavailability of key bioactive compounds, such as polyphenols and dietary fibers, is limited by their binding with antinutritional factors like phytic acid, necessitating strategies like germination or thermal processing to mitigate these effects (GuanQing *et al.,* 2022). Future research should focus on refining extraction methods to preserve heat-sensitive nutrients while improving solubility and absorption in the gastrointestinal tract (Zhang *et al.,* 2025). The nutraceutical applications of foxtail millet are promising, yet further studies are needed to validate its health benefits, including anti-diabetic, antioxidant and anti-inflammatory properties, through well-designed clinical trials (Ingle *et al.,* 2023). Another key direction is the development of fortified foxtail millet-based products, leveraging nanoencapsulation or fermentation to enhance stability and targeted delivery of bioactive compounds (Sapara, *et al.,* 2024). Collaborative efforts between food scientists, nutritionists and industry stakeholders are essential to scale up production while maintaining cost-effectiveness and consumer acceptance (Zhang *et al.,* 2025). Addressing these challenges will position foxtail millet as a sustainable, functional food in global markets (Zhang *et al.,* 2025).

CONCLUSION

Foxtail millet stands out as a nutritional powerhouse, offering a remarkable combination of health-promoting bioactive compounds and essential nutrients. Its unique phytochemical profile, including diverse phenolic compounds, flavonoids and high-quality proteins, contributes to significant antioxidant, anti-inflammatory and metabolic regulatory properties. Advanced analytical techniques have revealed how processing methods like germination and fermentation can enhance these beneficial components, while modern omics technologies have deepened our understanding of their mechanisms of action in human health. The grain's gluten-free nature and low glycemic index further increase its appeal as a functional food for modern dietary needs. As research continues to uncover its full potential, foxtail millet emerges as both a sustainable crop solution and a valuable dietary component for preventing nutrition-related disorders, bridging traditional food with contemporary nutritional science. Its versatility in food applications positions it as an ideal candidate for addressing global nutritional challenges while meeting the growing demand for health-focused, plant-based food options.

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Informed consent

All animal procedures for experiments were approved by the Committee of Experimental Animal care and handling techniques were approved by the University of Animal Care Committee.

Conflict of interest

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