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## Millets in human health: Nutritional composition, bioactive phytochemicals and pharmacological mechanisms

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### Abstract

Millets, a diverse group of small-seeded cereals belonging to the family Poaceae, have re-emerged as nutritionally superior and climate-resilient grains with significant relevance to global food and health security. India, being the world's largest producer of millets, plays a pivotal role in promoting these crops as sustainable alternatives to refined cereals. Millets are rich in complex carbohydrates, dietary fiber, high-quality proteins, essential minerals, vitamins and a wide spectrum of phytochemicals, justifying their recognition as nutri-cereals. Their low glycemic index, slow digestibility and high fiber content make them particularly beneficial in the management of diabetes, obesity, metabolic syndrome and cardiovascular disorders. Additionally, millets exhibit potent antioxidant, anti-inflammatory, anticancer, neuroprotective, immunomodulatory and detoxifying properties due to the presence of phenolic acids, flavonoids, tannins, phytosterols and bioactive peptides. Despite their nutritional richness, the presence of antinutritional factors such as phytates, tannins and oxalates can limit mineral and protein bioavailability. However, traditional and modern processing techniques including soaking, fermentation, germination, malting and enzymatic treatments have been shown to significantly reduce these antinutrients while enhancing nutrient and phytochemical bioavailability. Advances in food processing and formulation have facilitated the development of millet-based functional foods, gluten-free products and nutraceuticals, expanding their application in therapeutic nutrition and special diets. Millet-derived bioactive extracts and value-added products further strengthen their potential in disease prevention and health promotion. This review comprehensively consolidates current knowledge on the nutritional composition, pharmacological activities, bioavailability challenges, functional food applications and nutraceutical potential of millets, while also identifying critical research gaps related to clinical validation, bioactive standardization and consumer acceptability. Strengthening multidisciplinary research, policy support and industry collaboration will be essential to fully harness the health-promoting and sustainability potential of millets in modern food systems.

### 1. Introduction

India occupies a pivotal position in global millet production, contributing nearly 38.4% of the world's total millet output according to FAO estimates. This dominance reflects the country's diverse agroecological conditions and the long history of millet cultivation across rainfed and marginal farming systems. Millets constitute a major component of India's traditional cereal basket and include sorghum (*Sorghum bicolor*), pearl millet (*Pennisetum glaucum*), finger millet (*Eleusine coracana*), along with several small millets such as foxtail (*Setaria italica*), kodo (*Paspalum scrobiculatum*), barnyard (*Echinochloa* spp.), little (*Panicum sumatrense*) and proso millet (*Panicum miliaceum*). These crops play a vital role in ensuring food and nutritional security, particularly among resource-poor populations residing in arid and semi-arid regions of the country. At the national level, millet cultivation is widely distributed, with

Rajasthan emerging as the leading producer, followed by Uttar Pradesh, Karnataka and Maharashtra. However, temporal analyses indicate considerable fluctuations in the area, production and productivity of millets across India. These variations are primarily attributed to climatic variability, market forces, policy shifts and competition from high-yielding irrigated cereals such as rice and wheat. Agronomic studies assessing growth rates and instability indices have demonstrated that while productivity gains have been achieved in certain states due to improved varieties and agronomic interventions, the overall area under millets has shown inconsistent trends over time (Banerjee *et al.*, 2024). Such findings highlight the need for sustained policy support and technological innovation to stabilize millet production systems. A comprehensive national assessment of millet cultivation further documents the spatial distribution of millet area and production across Indian states, emphasizing their strategic importance in the context of food security, climate resilience and export potential (Banerjee *et al.*, 2024). Millets are increasingly recognized as climate-smart crops due to their inherent tolerance to drought, heat stress and low soil fertility. Their ability to produce reasonable yields under minimal input conditions makes them particularly suitable for rainfed agriculture, which constitutes a significant proportion of India's cultivated land. In the face of climate change and increasing water scarcity, millets offer a sustainable alternative to water-intensive cereal crops.

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Beyond their agronomic advantages, millets have gained renewed global attention for their exceptional nutritional quality, leading to their classification as nutri-cereals. This designation reflects their richness in essential nutrients required for optimal human health. Millets are nutritionally superior to refined cereals, as they contain higher levels of dietary fiber, quality protein, essential amino acids, vitamins, minerals and a wide range of bioactive compounds. Major and minor millets collectively contribute to improved dietary diversity and nutritional adequacy, especially in populations vulnerable to micronutrient deficiencies (Dayakar Rao *et al.*, 2017). The protein content of millets is moderate to high and is characterized by a relatively balanced amino acid composition, including sulfur-containing amino acids such as methionine and cysteine, which are limited in many other cereals. Although, lysine content is comparatively low, the overall protein quality of millets improves significantly when consumed in combination with legumes and pulses. In addition to protein, millets are rich in complex carbohydrates, particularly slowly digestible starch and resistant starch fractions. These carbohydrate characteristics contribute to sustained energy release and reduced postprandial glucose spikes, enhancing their suitability for individuals with metabolic disorders. Dietary fiber is one of the most distinguishing nutritional features of millets. Both soluble and insoluble fiber fractions are present in substantial amounts, with finger millet and pearl millet exhibiting particularly high fiber content. Increased dietary fiber intake is strongly associated with improved gastrointestinal health, enhanced satiety, reduced serum cholesterol levels and better glycemic regulation. The consumption of fiber-rich millets promotes beneficial gut microbiota and supports digestive health, thereby reducing the risk of gastrointestinal disorders (Dayakar Rao *et al.*, 2017). Millets are also notable for their micronutrient density. They serve as excellent sources of minerals such as iron, calcium, zinc, magnesium, phosphorus and potassium. Finger millet is especially valued for its exceptionally high calcium content, making it beneficial for bone health, particularly among children, women and elderly populations. Pearl millet is rich in iron and zinc, contributing to the prevention of anemia and supporting immune function. Additionally, millets contain significant amounts of B-complex vitamins, including thiamine, riboflavin, niacin and folic acid, which play crucial roles in energy metabolism and nervous system function (Dayakar Rao *et al.*, 2017).

Apart from macro and micronutrients, millets are rich in phytochemicals such as phenolic acids, flavonoids, tannins and phytosterols. These bioactive compounds are largely concentrated in the outer layers of the grain, which are retained during whole-grain consumption. Phenolic acids such as ferulic, p-coumaric, caffeic and vanillic acids contribute significantly to the antioxidant capacity of millets. Although, some phytochemicals like tannins and phytates have traditionally been considered antinutritional factors, contemporary research recognizes their protective roles against oxidative stress, inflammation and chronic diseases (Dayakar Rao *et al.*, 2017). The antioxidant potential of millets plays a central role in their health-promoting properties. Oxidative stress is implicated in the development of several chronic diseases, including cardiovascular diseases, diabetes, cancer and neurodegenerative disorders. The bioactive compounds present in millets scavenge free radicals and enhance endogenous antioxidant defenses, thereby reducing cellular damage. Regular consumption of millet-based diets has been associated with improved antioxidant status and reduced oxidative stress

markers, underscoring their relevance in preventive nutrition. Millets also exhibit notable anti-inflammatory effects through the modulation of inflammatory pathways and mediators. Chronic low-grade inflammation is a key contributor to the pathogenesis of lifestyle-related disorders and dietary strategies aimed at reducing inflammation are increasingly emphasized. The phenolic compounds present in millets inhibit pro-inflammatory enzymes and cytokines, thereby contributing to improved metabolic and cardiovascular health.

One of the most significant functional attributes of millets is their low glycemic index. The presence of dietary fiber, resistant starch and slowly digestible carbohydrates results in delayed glucose absorption and reduced postprandial blood glucose levels. This property makes millets particularly beneficial for individuals with diabetes mellitus and those at risk of developing insulin resistance. Replacing refined cereals with millet-based foods has been shown to improve glycemic control and metabolic outcomes, highlighting their therapeutic potential in diet-based disease management. Millets also contribute to cardiovascular health through multiple mechanisms. Their high fiber content, presence of phytosterols and antioxidant activity collectively help lower serum cholesterol levels, improve lipid profiles and reduce the risk of atherosclerosis. Regular intake of whole-grain millets is associated with reduced incidence of cardiovascular diseases, supporting their inclusion in heart-healthy diets. From a functional perspective, millets possess desirable processing characteristics that enable their incorporation into a wide range of traditional and modern food products. They are used in porridges, flatbreads, fermented foods, snacks, bakery items and beverages. Advances in food processing technologies such as malting, fermentation, extrusion and composite flour formulation have further enhanced the acceptability and nutritional value of millet-based products. Their gluten-free nature adds to their appeal, particularly for individuals with celiac disease or gluten intolerance. In addition to nutritional and health benefits, millets align strongly with sustainability goals. Their low water and input requirements, adaptability to marginal lands and reduced environmental footprint make them ideal crops for sustainable agriculture. Promoting millet cultivation supports agrobiodiversity, enhances farmer resilience and contributes to climate change mitigation strategies.

## 2. Nutritional importance of millets

Millets are increasingly recognized as nutritionally superior cereals due to their dense and diverse nutrient composition. Compared with commonly consumed staple grains such as polished rice and refined wheat, millets provide significantly higher amounts of dietary fiber, essential minerals, vitamins and bioactive compounds. This unique nutritional profile has led to their classification as “nutri-cereals,” reflecting their capacity to enhance dietary quality and address multiple forms of malnutrition. Traditional food systems in Asia and Africa have long relied on millets as staple foods and contemporary nutrition science now validates their importance in promoting health and preventing diet-related disorders (Dayakar Rao *et al.*, 2017). One of the most prominent nutritional advantages of millets is their high dietary fiber content. Millets contain both soluble and insoluble fiber fractions, which play complementary roles in human health. Insoluble fiber improves bowel movement, increases fecal bulk and reduces the risk of constipation and colorectal disorders, while soluble fiber helps regulate blood glucose and cholesterol levels. The regular consumption of fiber-rich millet-based diets promotes digestive

health, enhances satiety and supports healthy weight management by reducing overall calorie intake. Unlike refined cereals, which lose much of their fiber during milling, millets are often consumed as whole grains, ensuring retention of their fiber-rich outer layers (Dayakar Rao *et al.*, 2017). Dietary fiber in millets also contributes significantly to improved metabolic regulation. High-fiber foods slow gastric emptying and carbohydrate digestion, leading to gradual glucose absorption and stable postprandial blood sugar levels. This property is particularly beneficial for individuals with diabetes mellitus and insulin resistance. The sustained release of energy from millet-based foods helps prevent rapid spikes and crashes in blood glucose, thereby supporting long-term glycemic control. As a result, millets are increasingly recommended as part of diabetic-friendly and low-glycemic diets.

In addition to fiber, millets provide moderate to high amounts of plant-based protein with a relatively balanced amino acid composition. Millet proteins contain appreciable levels of essential amino acids such as methionine, cysteine and tryptophan, which are often limited in other cereal grains. Although, lysine content is comparatively lower, the protein quality of millets improves substantially when consumed alongside pulses and legumes, a combination commonly found in traditional diets. The inclusion of millets in daily meals thus contributes meaningfully to meeting protein requirements, especially in vegetarian and resource-limited populations (Dayakar Rao *et al.*, 2017). Millets are also important sources of essential minerals that play critical roles in physiological functioning. Among these, calcium, iron, zinc, magnesium, phosphorus and potassium are present in significantly higher concentrations than in rice and wheat. Finger millet (*E. coracana*) is particularly notable for its exceptionally high calcium content, making it one of the richest plant-based sources of dietary calcium. Adequate calcium intake is essential for bone mineralization, skeletal development and the prevention of osteoporosis, especially among children, women and elderly individuals. The inclusion of finger millet in regular diets can therefore contribute to improved bone health and reduced risk of calcium deficiency disorders (Dayakar Rao *et al.*, 2017). Iron deficiency anemia remains a major public health concern in many developing countries, particularly among women and children. Millets such as pearl millet (*P. glaucum*) and sorghum (*S. bicolor*) contain substantial amounts of iron and zinc, which are essential for hemoglobin synthesis, oxygen transport, immune function and enzymatic activity. Regular consumption of iron-rich millets can help improve hemoglobin levels and reduce the prevalence of anemia when combined with appropriate dietary practices that enhance mineral bioavailability. Zinc present in millets further supports immune response, growth and cellular repair mechanisms.

Magnesium and potassium, also abundant in millets, play vital roles in muscle function, nerve transmission and cardiovascular regulation. Magnesium acts as a cofactor for numerous enzymes involved in energy metabolism, protein synthesis and glucose regulation, while potassium helps maintain electrolyte balance and normal blood pressure. The inclusion of millets in the diet therefore supports cardiovascular health and reduces the risk of hypertension and related disorders. Millets are also rich in B-complex vitamins, including thiamine (vitamin B), riboflavin (vitamin B<sub>2</sub>), niacin (vitamin B<sub>3</sub>) and folic acid. These vitamins are essential for energy metabolism, nervous system function, red blood cell formation and overall cellular health. Thiamine plays a key role in carbohydrate metabolism,

riboflavin supports cellular respiration and niacin contributes to lipid metabolism and DNA repair. Folic acid is particularly important for pregnant women, as it supports fetal development and prevents neural tube defects. The presence of these vitamins further enhances the nutritional significance of millets as wholesome staple foods (Dayakar Rao *et al.*, 2017). Another important nutritional attribute of millets is their natural gluten-free nature. Unlike wheat, barley and rye, millets do not contain gluten proteins, making them suitable for individuals with celiac disease or gluten sensitivity. Gluten intolerance is increasingly recognized worldwide and the demand for nutritious gluten-free alternatives is growing rapidly. Millets offer a valuable solution, as they provide not only gluten-free carbohydrates but also superior fiber, mineral and micronutrient content compared to many refined gluten-free products. This characteristic broadens their applicability in clinical nutrition and specialized dietary interventions. Beyond their macro- and micronutrient content, millets are rich in bioactive phytochemicals that contribute to their antioxidant and protective properties. These include phenolic acids, flavonoids, tannins and phytosterols, which are primarily concentrated in the seed coat and outer layers of the grain. Phenolic compounds such as ferulic acid, caffeic acid and p-coumaric acid exhibit strong antioxidant activity by neutralizing free radicals and reducing oxidative stress. Oxidative stress is a key factor in the development of chronic diseases such as cardiovascular disorders, diabetes, cancer and neurodegenerative conditions. The regular intake of antioxidant-rich millets can therefore help protect cells from oxidative damage and support long-term health (Dayakar Rao *et al.*, 2017).

In addition to diabetes management, millet consumption has been linked to improved digestive efficiency and gut health. Dietary fiber acts as a prebiotic substrate, promoting the growth of beneficial gut microbiota. A healthy gut microbiome is increasingly recognized as a key determinant of overall health, influencing immune function, metabolism and even mental well-being. By supporting gut microbial balance, millets contribute indirectly to improved immunity and reduced inflammation. Different millet varieties also offer specific nutritional advantages that can be leveraged to address targeted health concerns. For instance, finger millet supports bone health due to its high calcium content, pearl millet aids in anemia prevention due to its iron richness and foxtail and little millets are particularly beneficial for glycemic control. This diversity allows millets to be strategically incorporated into diets based on nutritional needs, age groups and health conditions. The cumulative nutritional benefits of millets have led to their recognition as effective tools for combating both undernutrition and overnutrition. In resource-poor settings, millets provide affordable sources of essential nutrients, helping address protein-energy malnutrition and micronutrient deficiencies. In contrast, in urban and affluent populations, millets support the prevention and management of lifestyle-related disorders such as obesity, diabetes and cardiovascular diseases. This dual relevance highlights their importance across socio-economic contexts.

### 3. Nutritional profile of millets

Millets are increasingly recognized as nutritionally superior cereals owing to their well-balanced macronutrient composition, rich micronutrient density and abundance of health-promoting phytochemicals. Unlike refined cereals, millets are generally consumed in whole or minimally processed forms, allowing them to retain their

bran, germ and endosperm components. This structural integrity contributes significantly to their nutritional value and functional health benefits. The combined presence of complex carbohydrates, quality proteins, essential minerals, vitamins and bioactive compounds positions millets as nutritionally complete grains with strong relevance in both traditional diets and modern functional food systems.

### 3.1 Macronutrients

Millets are characterized by a balanced macronutrient profile that supports sustained energy release and metabolic health. Carbohydrates constitute the major component of millet grains, typically accounting for 60-70% of their total composition. However, unlike polished rice and refined wheat products, the carbohydrates in millets are predominantly complex in nature. They include slowly digestible starch, resistant starch and substantial amounts of dietary fiber. This unique carbohydrate structure delays digestion and glucose absorption, resulting in a lower glycemic response and prolonged energy availability. Consequently, millet-based diets are particularly beneficial for individuals managing diabetes, obesity and metabolic syndrome. Dietary fiber is one of the most distinguishing macronutrient components of millets. Both soluble and insoluble fiber fractions are present in appreciable quantities, contributing to multiple physiological benefits. Insoluble fiber enhances bowel motility, increases fecal bulk and promotes regular bowel movements, thereby supporting gastrointestinal health. Soluble fiber, on the other hand, plays a key role in regulating blood glucose and lipid levels by slowing nutrient absorption and binding bile acids. The high fiber content of millets also enhances satiety, helping to reduce overall caloric intake and support weight management strategies. Protein content in millets generally ranges from 7-13%, depending on the species and variety. Although, this level is lower than that of legumes, millet proteins offer a relatively good balance of essential amino acids compared to rice and wheat. Notably, certain millets such as finger millet and foxtail millet contain higher levels of methionine, a sulfur-containing amino acid that is often limiting in other cereals. This makes millets nutritionally complementary when consumed alongside legumes, a dietary pattern commonly observed in traditional food systems. The digestibility of millet proteins further enhances their contribution to dietary protein intake, particularly in plant-based and vegetarian diets. The fat content of millets is modest, typically ranging between 3-5%, but is nutritionally advantageous due to its favorable fatty acid composition. Millet lipids are rich in unsaturated fatty acids, particularly linoleic acid, which is essential for maintaining cell membrane integrity and supporting cardiovascular health. In addition, millets contain natural antioxidants such as tocopherols (vitamin E), which protect lipids from oxidative degradation. These antioxidants not only contribute to human health but also enhance the storage stability of millet grains by reducing lipid peroxidation. Collectively, the macronutrient composition of millets supports metabolic balance, cardiovascular health and long-term energy regulation, reinforcing their role as functional staple foods.

### 3.2 Micronutrients

Millets are exceptionally rich sources of essential minerals, often surpassing commonly consumed cereals such as rice and wheat in mineral density. According to the ICAR-Indian Institute of Millets Research, millets contain substantial amounts of calcium, iron, zinc, magnesium, phosphorus and potassium, all of which are vital for

maintaining physiological homeostasis. These minerals play crucial roles in bone formation, oxygen transport, immune response, nerve function and enzymatic reactions. Finger millet (*E. coracana*) is particularly distinguished by its remarkably high calcium content, which is significantly greater than that of most other cereals. Adequate calcium intake is essential for skeletal development, bone mineralization and the prevention of osteoporosis, especially among children, women and elderly individuals. The regular inclusion of finger millet in diets can therefore contribute to improved bone health and reduced risk of calcium deficiency-related disorders. Iron and zinc deficiencies are widespread nutritional challenges, particularly in developing countries. Millets such as pearl millet (*P. glaucum*) and sorghum (*S. bicolor*) are rich sources of these essential trace elements. Iron is critical for hemoglobin synthesis and oxygen transport, while zinc plays a central role in immune function, growth and cellular repair. Comparative studies indicate that millets generally possess higher concentrations of these minerals than conventional cereals, making them valuable tools for addressing micronutrient malnutrition in vulnerable populations (Bhoyar, 2023). In addition to minerals, millets are important sources of vitamins, particularly B-complex vitamins such as thiamine, riboflavin, niacin and folate. These vitamins are integral to energy metabolism, nervous system function and red blood cell production. Thiamine supports carbohydrate metabolism, riboflavin is involved in cellular respiration and niacin contributes to lipid metabolism and DNA repair. Folate is especially important for pregnant women, as it supports fetal development and reduces the risk of neural tube defects. The ICAR report also highlights the presence of natural antioxidant vitamins, including vitamin E (tocopherols), which help reduce oxidative stress and support cellular health. Since these vitamins are concentrated in the bran layers, whole-grain millets offer significant nutritional advantages over refined cereals that lose most micronutrients during processing.

### 3.3 Phytochemicals and bioactive compounds

Beyond conventional nutrients, millets are rich in a wide array of phytochemicals and bioactive compounds that contribute substantially to their health-promoting properties. These include phenolic acids, flavonoids, tannins, phytosterols, lignans and bioactive peptides. A recent review highlights that millets contain considerable levels of polyphenols and antioxidants, with ferulic acid identified as the most predominant phenolic acid across various millet species, followed by caffeic acid (Babypriyanka *et al.*, 2025). These phenolic compounds occur in both free and bound forms, with bound phenolics being particularly abundant in whole-grain millets. The antioxidant capacity of millets is closely associated with their phenolic and flavonoid content. Studies indicate that millets such as browntop millet possess especially high levels of phenolics and dietary fiber concentrated in the bran layer, which significantly enhances their free radical scavenging ability (Vakte *et al.*, 2023). Flavonoids such as catechins, quercetin and apigenin further strengthen the antioxidant and anti-inflammatory potential of millets by modulating oxidative stress pathways and inhibiting pro-inflammatory mediators. In addition to phenolics, millets contain several other bioactive compounds of nutraceutical importance. These include phytosterols, which help reduce cholesterol absorption and improve lipid profiles; lignans, which exhibit antioxidant and hormone-modulating properties; and bioactive peptides, which demonstrate antihypertensive and antidiabetic effects. A comprehen-

sive review emphasizes that the bioactive profile of millets contributes to improved lipid metabolism, enhanced immune function and better glycemic control (Babypriyanka *et al.*, 2025). The bioavailability and efficacy of millet phytochemicals can be further enhanced through appropriate processing techniques. Methods such as fermentation, germination, malting and enzymatic hydrolysis have been shown to increase the release of bound phenolics and improve mineral absorption by reducing antinutritional factors. These processing approaches not only enhance the nutritional and therapeutic potential of millets but also improve their sensory qualities and consumer acceptability. Overall, the rich phytochemical and bioactive composition of millets underscores their classification as functional grains with significant potential in chronic disease prevention. By modulating oxidative stress, inflammation, lipid metabolism and glucose homeostasis, millets contribute to improved metabolic health and long-term well-being. Their integration into regular diets therefore represents a scientifically supported strategy for promoting health through nutrition.

#### 4. Pharmacological activities of millets

Millets exhibit a broad spectrum of pharmacological activities due to their low glycemic index, high dietary fiber, essential micronutrients and rich phytochemical composition. Their slow-digesting carbohydrates regulate glucose metabolism, while dietary fiber supports gut health and lipid regulation. The presence of minerals such as iron, calcium, magnesium and zinc helps prevent anemia, bone disorders and immune dysfunction. Additionally, phenolic acids, flavonoids and tannins provide antioxidant and anti-inflammatory effects, offering protection against cardiovascular diseases, cancers, metabolic disorders and neurodegenerative conditions. Collectively, these attributes position millets as functional foods with preventive and therapeutic relevance in chronic disease management (Gupta and Mishra, 2024; Jacob *et al.*, 2024).

##### 4.1 Diabetes mellitus and metabolic disorders

Millets play a significant role in the dietary management of diabetes mellitus due to their low glycemic index (GI), high dietary fiber, resistant starch and polyphenolic compounds. Their complex carbohydrates digest slowly, reducing glucose absorption rates and preventing postprandial glucose spikes. A systematic review reported that millet-based diets significantly lower postprandial blood glucose by delaying gastric emptying and enhancing insulin sensitivity, making them effective in type 2 diabetes management (Mahendran and Krishnaja, 2025). Evidence from Indian nutrition and intervention studies indicates that regular millet consumption can reduce postprandial glucose levels by approximately 15% and decrease glycated hemoglobin (HbA1c) by 7-10%, demonstrating their therapeutic potential for long-term glycemic control. Polyphenols present in millets inhibit carbohydrate-hydrolyzing enzymes such as  $\alpha$ -amylase and  $\alpha$ -glucosidase, further contributing to improved glucose homeostasis (Mahendran and Krishnaja, 2025). Beyond diabetes, millets contribute to the prevention and management of metabolic disorders including obesity, dyslipidemia and metabolic syndrome. Their high fiber content enhances satiety, reduces energy intake and supports weight management. Reviews on lifestyle disorders highlight that millet bioactives regulate lipid metabolism, reduce oxidative stress and improve cardiovascular markers such as serum cholesterol and triglycerides (Gupta and Mishra, 2024). These

combined effects position millets as functional foods capable of restoring metabolic balance.

##### 4.2 Gastrointestinal disorders and gut health

Millets significantly improve gastrointestinal health due to their high dietary fiber content, prebiotic compounds and anti-inflammatory phytochemicals. Comparative nutritional analyses show that millets contain 15-20% more dietary fiber than rice and wheat, enhancing bowel motility, stool bulk and regularity. These properties are beneficial in managing constipation, indigestion and irritable bowel syndrome (IBS) (Gupta and Mishra, 2024). Millet-derived fibers also promote the growth of beneficial gut microbiota, including *Lactobacillus* and *Bifidobacterium* species, which support intestinal integrity and immune modulation. Bioactive compounds present in millets strengthen the intestinal barrier, reduce gut inflammation and lower intestinal permeability, thereby helping manage conditions such as leaky gut syndrome. Their naturally gluten-free nature further makes millets suitable for individuals with gluten sensitivity or celiac-related gastrointestinal disorders (Jacob *et al.*, 2024).

##### 4.3 Cancer prevention and modulation

Millets contribute to cancer prevention primarily through their high dietary fiber, antioxidant and phytochemical content. Dietary fiber reduces intestinal transit time and limits exposure of gut epithelial cells to carcinogens. A recent review reports that millets contain substantial amounts of polyphenols, flavonoids and phenolic acids that exhibit strong antioxidant activity and suppress tumor initiation and progression by protecting DNA from oxidative damage (Pavithra *et al.*, 2025). The low glycemic index of millets further contributes to cancer risk reduction by regulating insulin and insulin-like growth factor signaling pathways associated with tumor development. Experimental studies demonstrate that polyphenol-rich extracts from pearl millet inhibit breast cancer cell proliferation and induce apoptosis through mitochondrial-mediated pathways (Hajri *et al.*, 2024). Additionally, phytochemicals such as tannins, lignans and phytosterols exert anti-inflammatory, antiproliferative and antiangiogenic effects, supporting the role of millets in cancer modulation.

##### 4.4 Detoxification and systemic protection

Millets play a vital role in detoxification through their high dietary fiber, antioxidant capacity and mineral content. Dietary fiber facilitates the binding and elimination of metabolic waste products and environmental toxins *via* the gastrointestinal tract. A comprehensive review reports that millets are rich in phenolics, flavonoids and anthocyanidins that neutralize reactive oxygen species and reduce toxin-induced oxidative damage (Jacob *et al.*, 2024). Millets also support hepatic detoxification by enhancing antioxidant enzyme activity and reducing oxidative load on liver cells. Essential minerals such as magnesium, zinc, copper and selenium present in millets act as cofactors for detoxifying enzymes. Beyond detoxification, millet bioactives protect tissues from chronic inflammation and oxidative stress, reducing the risk of degenerative diseases linked to toxin accumulation (Suman, 2024).

##### 4.5 Cardiovascular health and hypertension

Millets exhibit cardioprotective effects through lipid modulation, antioxidant activity and blood pressure regulation. Soluble fiber

reduces intestinal cholesterol absorption, while phytosterols inhibit cholesterol uptake. Antioxidants present in millets prevent low-density lipoprotein (LDL) oxidation, a key step in atherosclerosis development (Gupta and Mishra, 2024). The high potassium and magnesium content of millets contributes to vasodilation and blood pressure control, making them beneficial for individuals with hypertension. Regular millet consumption has been associated with improved lipid profiles, reduced arterial stiffness and enhanced endothelial function, collectively lowering cardiovascular disease risk (Jacob *et al.*, 2024).

#### 4.6 Anti-inflammatory and antioxidant activities

Chronic inflammation and oxidative stress are central mechanisms underlying many non-communicable diseases. Millets possess strong antioxidant and anti-inflammatory properties due to their high phenolic and flavonoid content. These compounds inhibit inflammatory mediators such as cyclooxygenase (COX), lipoxygenase (LOX) and nuclear factor-kappa B (NF- $\kappa$ B), reducing systemic inflammation (Suman, 2024). Millet antioxidants also enhance endogenous defense systems by increasing the activity of antioxidant enzymes, thereby maintaining redox balance and protecting cellular components from oxidative damage (Jacob *et al.*, 2024).

#### 4.7 Neuroprotective and cognitive health benefits

Millets support neurological health through antioxidant, anti-inflammatory and micronutrient-mediated mechanisms. Minerals such as magnesium, zinc and iron, along with B-complex vitamins, play crucial roles in neurotransmission, cognitive function and neuronal protection. Polyphenols in millets protect neurons from oxidative stress and modulate neuroinflammatory pathways associated with neurodegenerative disorders (Pavithra *et al.*, 2025). Stable glucose release from low-GI millets also supports sustained brain energy metabolism, reducing cognitive fatigue and metabolic stress.

#### 4.8 Immune modulation and antimicrobial activity

Millets enhance immune function by supplying essential micronutrients such as zinc, iron and selenium, which are vital for immune cell proliferation and antioxidant defense. Dietary fiber supports gut-associated lymphoid tissue (GALT), strengthening mucosal immunity. Certain millet phytochemicals exhibit antimicrobial activity against pathogenic bacteria, contributing to gut and systemic immune defense (Gupta and Mishra, 2024).

#### 4.9 Antiageing and longevity promotion

Millets contribute to healthy aging by reducing oxidative stress, chronic inflammation and metabolic dysfunction. Their antioxidants protect cellular DNA, proteins and lipids from age-related damage. Bioactive compounds modulate signaling pathways involved in aging and mitochondrial function, supporting longevity and physiological resilience (Suman, 2024; Jacob *et al.*, 2024).

### 5. Bioavailability and antinutritional factors in millets

Millets are nutritionally rich cereals; however, like many plant-based foods, their full nutritional potential is influenced by the presence of antinutritional factors that can affect nutrient bioavailability. Bioavailability refers to the proportion of nutrients that are digested, absorbed and utilized by the body. Although, millets contain high levels of minerals, proteins and phytochemicals, the absorption and

utilization of these nutrients can be limited by compounds such as phytates, tannins, oxalates and enzyme inhibitors. Understanding the nature of these antinutritional factors, their physiological effects and the role of processing techniques in mitigating their impact is essential for maximizing the health benefits of millets. Contemporary research increasingly emphasizes that appropriate processing can substantially reduce antinutritional effects while simultaneously enhancing nutrient and phytochemical bioavailability, reinforcing the functional and nutraceutical value of millets (Dayakar Rao *et al.*, 2017; Babypriyanka *et al.*, 2025).

#### 5.1 Antinutritional compounds in millets

Millets naturally contain several antinutritional compounds that serve protective roles in plants but can interfere with nutrient absorption in humans. Among these, phytates (phytic acid), tannins and oxalates are the most prominent. These compounds are primarily concentrated in the outer bran layers of millet grains, which explains their higher levels in whole-grain millets compared to polished cereals. While traditionally viewed as undesirable, recent research recognizes that these compounds also possess antioxidant and health-protective properties when present at moderate levels (Dayakar Rao *et al.*, 2017). Phytates are the primary storage form of phosphorus in millet seeds and are known to chelate divalent minerals such as iron, zinc, calcium and magnesium, forming insoluble complexes that reduce their intestinal absorption. Phytic acid content varies among millet species, with pearl millet and finger millet generally exhibiting higher levels due to their dense bran structure. Despite their mineral-binding properties, phytates also exhibit antioxidant activity and may protect against oxidative stress and certain chronic diseases when consumed as part of a balanced diet (Bhoyar, 2023). Tannins are polyphenolic compounds widely present in millets, particularly in sorghum and some minor millets. They have a strong affinity for proteins and digestive enzymes, which can reduce protein digestibility and enzyme activity. Tannins are responsible for the characteristic astringency of certain millet varieties. However, they also exhibit potent antioxidant, anti-inflammatory and antimicrobial properties, contributing to disease prevention and gut health when consumed in appropriate quantities (Babypriyanka *et al.*, 2025). Oxalates are organic acids found in varying concentrations in millets, especially in finger millet. They can bind calcium to form insoluble calcium oxalate complexes, potentially reducing calcium bioavailability. Nevertheless, oxalates are generally present at moderate levels in millets and are significantly reduced through household processing methods. Importantly, oxalates also contribute to metal ion regulation and oxidative stress modulation, suggesting a dual role in nutrition and health (Dayakar Rao *et al.*, 2017).

#### 5.2 Impact of antinutrients on mineral and protein bioavailability

The presence of antinutritional factors in millets can influence the bioavailability of essential minerals and proteins, particularly in populations relying heavily on cereal-based diets. Phytates are the most extensively studied antinutrients affecting mineral absorption. By forming insoluble complexes with iron, zinc and calcium in the gastrointestinal tract, phytates reduce the fraction of these minerals available for absorption. This effect is particularly relevant in regions with high prevalence of micronutrient deficiencies, where millets serve as staple foods (Bhoyar, 2023). Iron and zinc bioavailability are especially sensitive to phytate concentration. Although, millets

are inherently rich in these minerals, their absorption may be compromised in unprocessed forms. This paradoxical high mineral content but low bioavailability has historically contributed to concerns regarding millet-based diets. However, studies emphasize that the overall nutritional impact depends not only on total mineral content but also on food preparation methods and dietary diversity (Dayakar Rao *et al.*, 2017). Tannins primarily affect protein bioavailability by forming complexes with dietary proteins and digestive enzymes such as trypsin and amylase. These interactions reduce protein digestibility and amino acid availability. Sorghum varieties with high tannin content have been shown to exhibit lower protein digestibility compared to low-tannin varieties. Despite this, tannins also slow protein digestion, which may have beneficial metabolic effects such as improved satiety and moderated postprandial responses (Babyriyanka *et al.*, 2025). Oxalates influence calcium bioavailability by forming insoluble calcium oxalate salts that are poorly absorbed in the intestine. In finger millet, which is exceptionally rich in calcium, the presence of oxalates can partially reduce calcium absorption. However, processing methods such as soaking, fermentation and cooking significantly lower oxalate content, allowing substantial calcium uptake from millet-based diets (Dayakar Rao *et al.*, 2017). Importantly, recent nutritional perspectives emphasize that antinutritional factors do not act in isolation. Their impact is modulated by food matrix effects, gut microbiota composition and concurrent intake of enhancers such as vitamin C and organic acids. Thus, while antinutrients can reduce nutrient bioavailability under certain conditions, their effects can be effectively mitigated through appropriate dietary and processing strategies (Gupta and Mishra, 2024).

### 5.3 Processing techniques to reduce antinutritional factors

Traditional and modern processing techniques play a critical role in reducing antinutritional factors in millets and improving nutrient bioavailability. Indigenous food processing methods developed over centuries such as soaking, germination, fermentation, malting and cooking have been shown to significantly lower phytate, tannin and oxalate levels. These methods not only enhance nutritional quality but also improve sensory properties and digestibility (Dayakar Rao *et al.*, 2017). Soaking is one of the simplest and most effective household techniques for reducing phytates and soluble antinutrients. During soaking, water-soluble phytates and tannins leach into the soaking medium, resulting in partial reduction. Germination further enhances this effect by activating endogenous phytase enzymes, which hydrolyze phytic acid into lower inositol phosphates with reduced mineral-binding capacity. Germinated millets have been shown to exhibit significantly higher iron, zinc and calcium bioavailability compared to raw grains (Bhoyar, 2023). Fermentation is particularly effective in reducing antinutritional factors while enhancing bioactive compound availability. Microbial activity during fermentation produces organic acids such as lactic acid, which lower pH and promote phytate degradation. Fermented millet-based foods also exhibit improved protein digestibility and mineral absorption due to enzymatic breakdown of complex matrices. Additionally, fermentation enhances gut-friendly probiotic properties, further supporting nutrient utilization (Babyriyanka *et al.*, 2025). Thermal processing methods such as boiling, steaming, roasting and pressure cooking also contribute to the reduction of tannins and oxalates. Heat denatures protein-tannin complexes and reduces enzyme inhibitors, thereby improving protein digestibility. Although excessive

heat may cause some nutrient losses, optimized cooking practices strike a balance between antinutrient reduction and nutrient retention (Dayakar Rao *et al.*, 2017). Modern processing techniques, including extrusion cooking and enzymatic treatment, have gained attention for large-scale millet utilization. These methods effectively reduce antinutritional compounds while producing shelf-stable, nutrient-dense products suitable for urban consumption. Such approaches support the mainstreaming of millets in contemporary food systems (Gupta and Mishra, 2024).

### 5.4 Enhancement of nutrient and phytochemical bioavailability

Beyond reducing antinutritional factors, processing techniques significantly enhance the bioavailability of nutrients and phytochemicals in millets. The breakdown of cell wall components during germination and fermentation releases bound minerals and phenolic compounds, increasing their intestinal accessibility. Bound phenolics, which constitute a major fraction of millet antioxidants, are converted into free forms with higher bioavailability and biological activity (Babyriyanka *et al.*, 2025). Fermentation and germination also enhance protein digestibility by activating proteolytic enzymes that break down storage proteins into bioactive peptides and free amino acids. These peptides exhibit antihypertensive, antioxidant and immunomodulatory properties, further contributing to the pharmacological value of millets. Enhanced protein digestibility also supports improved nitrogen utilization, particularly in plant-based diets (Jacob *et al.*, 2024). Mineral bioavailability is further improved by the reduction of phytate-to-mineral molar ratios during processing. Studies show that processed millet products exhibit significantly higher iron and zinc absorption compared to raw forms, especially when combined with vitamin C-rich foods. This synergy is particularly relevant for addressing anemia and zinc deficiency in millet-consuming populations (Bhoyar, 2023). Processing also improves the bioavailability of lipid-soluble antioxidants such as tocopherols and phytosterols by disrupting lipid-protein complexes. These compounds play key roles in reducing oxidative stress, improving lipid metabolism and supporting cardiovascular health. Enhanced phytochemical bioavailability contributes to the anti-inflammatory, anticancer and anti-ageing effects of millets (Suman, 2024). Overall, the enhancement of nutrient and phytochemical bioavailability through processing transforms millets from nutrient-rich grains into highly bioeffective functional foods. When appropriately processed, millets offer optimal nutritional benefits with minimal antinutritional interference, supporting long-term health and disease prevention (Gupta and Mishra, 2024).

## 6. Millet-based functional foods and nutraceutical applications

The growing recognition of millets as nutrient-dense, climate-resilient and health-promoting grains has stimulated renewed interest in their use as functional foods and nutraceuticals. Beyond their traditional role as staple cereals, millets are increasingly incorporated into value-added food products designed to deliver specific health benefits. Their unique combination of low glycemic index carbohydrates, dietary fiber, essential minerals and bioactive phytochemicals positions millets as ideal candidates for functional food development. Advances in food processing, nutraceutical extraction and product formulation have further expanded the scope of millet utilization in therapeutic nutrition, special diets and preventive healthcare.

### 6.1 Millet-based traditional foods and therapeutic uses

Millets have been integral to traditional food systems across Asia and Africa for centuries, where they have been consumed not only as staple foods but also as therapeutic dietary components. Traditional millet-based foods such as rotis, porridges, gruels, fermented beverages and steamed products have long been associated with digestive health, sustained energy release and improved metabolic balance. Indigenous knowledge systems recognized millets for their cooling effect, digestive ease and ability to strengthen the body, particularly in hot and arid climates. In Indian traditional medicine and folk nutrition, millets such as finger millet (*E. coracana*) have been recommended for bone health, convalescence and lactating women due to their high calcium and iron content. Pearl millet (*P. glaucum*) has traditionally been used to enhance strength and endurance among agricultural laborers, while foxtail and little millets have been consumed during fasting and illness because of their easy digestibility and sustained energy release (Dayakar Rao *et al.*, 2017). Fermented millet foods such as dosa, idli, ambali and traditional beverages improve nutrient bioavailability and digestive tolerance. Fermentation reduces antinutritional factors and enhances the activity of beneficial microorganisms, contributing to gut health and immune support. Ethnographic and nutritional studies highlight that populations consuming traditional millet-based diets exhibit lower incidences of lifestyle-related disorders, including diabetes and cardiovascular diseases (Saleh *et al.*, 2013).

### 6.2 Development of millet-based functional foods

The shift toward health-conscious consumer behavior has accelerated the development of millet-based functional foods designed to deliver specific physiological benefits beyond basic nutrition. Functional foods formulated from millets target glycemic control, gut health, cardiovascular protection and antioxidant support. Their naturally low glycemic index and high fiber content make millets especially suitable for functional foods aimed at diabetes and weight management. Millet-based functional products include composite flours, breakfast cereals, ready-to-eat snacks, extruded products, bakery items, instant mixes and beverage formulations. Processing technologies such as extrusion cooking, malting, germination and fermentation are widely employed to improve texture, sensory quality and nutrient bioavailability. Studies demonstrate that extrusion of millet-based products enhances starch digestibility while retaining antioxidant activity, making them suitable for diabetic-friendly foods (Chandrasekara and Shahidi, 2012). Functional millet foods are often enriched with probiotics, prebiotics, legumes, or plant bioactives to enhance their therapeutic value. For example, millet-legume composite foods improve protein quality, while millet-based synbiotic foods support gut microbiota modulation. Research highlights that regular consumption of millet-based functional foods leads to improved lipid profiles, reduced oxidative stress and better glycemic responses (Taylor and Emmambux, 2008).

### 6.3 Gluten-free and special diet applications

Millets are naturally gluten-free cereals, making them highly valuable in the formulation of foods for individuals with celiac disease, gluten intolerance and wheat allergy. The global rise in gluten-related disorders has increased demand for nutritionally superior gluten-free alternatives and millets offer significant advantages over refined gluten-free products that are often low in fiber and micronutrients.

Millet-based gluten-free products include breads, cookies, pasta, noodles, snacks and infant foods. Their incorporation improves dietary fiber intake, mineral density and antioxidant content in gluten-free diets. Studies show that millet-based gluten-free formulations exhibit improved glycemic response, better satiety and enhanced digestive tolerance compared to rice- or corn-based gluten-free foods (Arendt and Dal Bello, 2008). Beyond gluten-free diets, millets are increasingly incorporated into special dietary regimens such as diabetic diets, geriatric nutrition, infant and maternal nutrition and sports nutrition. Their slow-digesting carbohydrates support sustained energy release, while their mineral richness aids muscle function and bone health. Clinical nutrition studies suggest that millet-based diets improve metabolic outcomes in individuals with insulin resistance and obesity (Kaur *et al.*, 2014).

### 6.4 Millet-derived nutraceuticals and bioactive extracts

In addition to whole and processed foods, millets serve as valuable sources of nutraceutical ingredients and bioactive extracts. Millet grains contain a wide range of health-promoting compounds, including phenolic acids, flavonoids, phytosterols, lignans, bioactive peptides and dietary fibers, which can be isolated and utilized in nutraceutical formulations. Phenolic-rich extracts from millets have demonstrated strong antioxidant, anti-inflammatory, antidiabetic and anticancer activities in *in vitro* and *in vivo* studies. Ferulic acid, caffeic acid and flavonoids extracted from millet bran exhibit free radical scavenging activity and protective effects against oxidative stress-related disorders (Babyriyanka *et al.*, 2025). Millet-derived peptides produced through enzymatic hydrolysis have shown antihypertensive and antioxidant properties, highlighting their potential in cardiovascular nutraceuticals. Millet bran, often considered a by-product, is increasingly recognized as a valuable nutraceutical raw material due to its high concentration of fiber and bioactives. Encapsulation technologies and nanodelivery systems are being explored to enhance the stability and bioavailability of millet-derived nutraceuticals. These innovations expand the application of millets beyond conventional foods into dietary supplements, functional beverages and therapeutic formulations (Shahidi and Ambigaipalan, 2015). Millet-based functional foods and nutraceuticals represent a convergence of traditional knowledge and modern food science. Their versatility in food formulation, suitability for special diets and rich bioactive profile make millets ideal candidates for addressing contemporary nutritional and health challenges. From traditional therapeutic foods to advanced nutraceutical extracts, millets offer sustainable, affordable and scientifically validated solutions for preventive healthcare and functional nutrition. The continued integration of millets into functional food systems and nutraceutical development holds significant promise for improving public health while supporting sustainable food systems.

## 7. Processing, bioavailability and formulation aspects

Millet processing plays a crucial role in enhancing nutritional quality, reducing antinutritional factors and improving functional properties. Traditional methods such as soaking, germination, fermentation and thermal treatments significantly reduce phytates, tannins and enzyme inhibitors, thereby improving digestibility and nutrient release. Recent advancements in non thermal processing including high pressure processing, pulsed electric fields and enzymatic bioprocessing have shown promise in preserving heat sensitive bioactives while improving starch functionality and antioxidant

properties. These processing innovations are particularly important for minor millets, which often contain higher levels of antinutrients but also richer profiles of phenolics and dietary fiber. Bioavailability of millet nutrients is strongly influenced by both intrinsic grain structure and the applied processing techniques. Millets contain bioactive compounds such as phenolic acids, flavonoids and dietary fibers, but their utilization is often limited by complex matrices and antinutritional components. Processing methods like fermentation and germination enhance the release and absorption of these bioactives by breaking down cell wall components and reducing chelating agents such as phytates (Akanbi, *et al.*, 2019). Additionally, thermal and non thermal bioprocessing can modify starch digestibility, influence glycemic response and make millets suitable for functional foods targeting metabolic health. Thus, optimizing processing conditions is essential for maximizing the health benefits associated with millet consumption. Formulation aspects of millets have gained increasing attention due to their potential in developing gluten free, low glycemic and nutrient dense food products. The functional properties of millet flours such as water absorption, gelatinization behavior and pasting characteristics are significantly altered by processing, influencing their suitability for bakery, extruded and beverage applications. Incorporating processed millet fractions into composite flours enhances texture, shelf-life and nutritional value of formulated foods. Moreover, emerging technologies in encapsulation and fortification are being explored to improve the stability and targeted delivery of millet bioactives in functional food formulations (Bheemaiah Balyatanda *et al.*, 2024; Nanje Gowda *et al.*, 2025). These formulation strategies position millets as versatile ingredients for health oriented product development.

## 8. Applications of millets in health-oriented food systems

Millets are increasingly integrated into health oriented food systems due to their rich nutrient profile, gluten free nature and functional bioactive compounds. Their high fiber, mineral density and antioxidant content make them suitable for developing foods aimed at improving metabolic health, reducing glycemic response and addressing micronutrient deficiencies. Reviews highlight that millets are nutritionally superior to many staple cereals, offering higher levels of iron, calcium and dietary fiber, which support their use in preventive nutrition and therapeutic diets (Sadh *et al.*, 2024). Fermented millet-based foods represent a major application area, as fermentation enhances nutrient bioavailability, reduces antinutrients and generates beneficial metabolites such as B vitamins, short chain fatty acids and bioactive peptides. These functional metabolites contribute to improved gut health, immune modulation and overall digestive wellness. Research shows that fermented millets promote beneficial gut microbiota including *Faecalibacterium*, *Bifidobacterium* and *Lactobacillus* while suppressing pathogenic species, making them ideal for probiotic and synbiotic food formulations. Millets are also being incorporated into a wide range of functional food products such as gluten free bakery items, health beverages, porridges, energy bars and nutraceutical formulations. Their slow digesting starch and high fiber content support the development of low glycemic foods targeted at diabetes management and weight control. Contemporary dietary research emphasizes that millet-based products align well with modern health focused eating patterns, offering both nutritional and functional advantages in sustainable food systems (Kumawat *et al.*, 2025; Jetawat *et al.*, 2025).

## 9. Future perspectives

Despite the growing scientific interest in millets and their recognition as climate-resilient, nutrient-dense and health-promoting cereals, several critical research gaps remain that limit their full utilization in nutrition, pharmacology and functional food development. Addressing these gaps through interdisciplinary and translational research will be essential to unlock the complete potential of millets in global food and health systems. One of the primary research gaps relates to the limited availability of large-scale, well-controlled human clinical trials validating the pharmacological and therapeutic effects of millets. While numerous *in vitro* and animal studies, along with short-term dietary interventions, have demonstrated antidiabetic, cardioprotective, antioxidant and anti-inflammatory effects, long-term randomized controlled trials (RCTs) are scarce. Most existing evidence is population-specific and regionally confined, making it difficult to generalize health claims across diverse age groups, ethnicities and dietary patterns. Future research should focus on long-term clinical studies evaluating millet-based diets on metabolic disorders, cardiovascular health, gut microbiota modulation, cancer risk reduction and neurocognitive outcomes. Another major gap lies in the understanding of bioavailability and metabolism of millet-derived phytochemicals. Although, millets are rich in phenolic acids, flavonoids, tannins and other bioactives, their absorption, biotransformation and tissue-level bioefficacy in humans remain poorly characterized. Many phytochemicals occur in bound forms and their release depends on processing methods and gut microbial activity. Advanced studies using metabolomics, nutrigenomics and gut microbiome profiling are needed to elucidate how millet bioactives interact with human metabolic pathways and contribute to disease prevention at the molecular level. The dual role of antinutritional factors such as phytates, tannins and oxalates represents another important research frontier. While traditionally viewed as inhibitors of mineral and protein bioavailability, emerging evidence suggests that these compounds also possess antioxidant, anticancer and metabolic regulatory properties. However, the threshold between beneficial and adverse effects is not well defined. Future research should aim to establish optimal processing conditions that selectively reduce antinutrient-related mineral chelation while preserving or enhancing their protective bioactivities. This balance is critical for maximizing both nutritional and pharmacological benefits. Another significant gap concerns consumer awareness, perception and dietary adoption. Despite strong scientific evidence, millet consumption remains limited in many urban and high-income populations due to perceptions related to taste, texture and convenience. Interdisciplinary research integrating nutrition science, behavioral studies and food innovation is required to design millet-based products that align with modern dietary preferences while retaining health benefits. Looking ahead, the future of millet research lies in a systems-based approach that integrates agriculture, nutrition, pharmacology, food technology and public health. Advances in omics technologies, artificial intelligence-driven breeding, personalized nutrition and microbiome research offer unprecedented opportunities to position millets as cornerstone foods for sustainable and preventive healthcare. Policy-driven research linking millet consumption with national nutrition programs, climate adaptation strategies and non-communicable disease prevention frameworks will further enhance their global relevance.

## 10. Conclusion

Millets represent a unique class of climate-resilient, nutrient-dense cereals with immense potential to address global challenges related to nutrition security, chronic diseases and sustainable agriculture. Their balanced macronutrient profile, rich micronutrient content and abundance of bioactive phytochemicals underpin a wide spectrum of pharmacological activities, including antidiabetic, cardioprotective, anti-inflammatory, antioxidant and anticancer effects. Although the presence of antinutritional factors can limit nutrient bioavailability, traditional and modern processing techniques effectively mitigate these constraints while enhancing functional efficacy. The integration of millets into functional foods, gluten-free products and nutraceutical formulations highlights their relevance in modern dietary systems. Addressing existing research gaps through clinical validation, advanced processing and bioavailability-focused studies will further strengthen the scientific basis for millet promotion. Overall, millets offer a sustainable, evidence-based solution for improving public health, supporting environmental resilience and advancing future food systems.

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## Conflict of interest

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

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