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A comprehensive review on exploring the nutritional profile of small millets

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Abstract

Small millets are the nutrient-rich crops that emerged as underutilized champions capable of transforming sustainable agriculture. These climate-resilient grains thrive in marginal environments where major cereals struggle, and are valued for their rich nutritional profile. They are packed with dietary fiber, protein, essential amino acids, and micronutrients such as iron and calcium. Their gluten-free nature and low glycemic index make them an excellent choice for managing metabolic disorders like diabetes and obesity. In addition to their bioactive compounds, including phenolics and flavonoids, which exhibit antioxidant, anti-inflammatory, and cardioprotective properties, small millets also possess prebiotic potential, promoting gut microbiota diversity and digestive health. Advances in nutritional genomics have enabled the identification of genes responsible for nutrient biosynthesis, accumulation, and bioavailability. Furthermore, biofortification strategies, including conventional breeding, molecular interventions, and agronomic fortification, are enhancing their nutritional profile to combat micronutrient deficiencies. Their resilience to harsh climatic conditions, low input requirements, and dual-purpose attributes of providing both high-quality grain and forage underscores their suitability for sustainable agriculture. This review of small millets brings together and articulates the nutritional value, functional benefits, nutritional genomic advancements, and biofortification approaches of small millets.

1. Introduction

Small millets are nutritionally rich, small-seeded grasses classified under the Poaceae family. They are the age-old crops domesticated for many decades (Singh *et al.*, 2020). Despite their superior nutrient composition, the trends in production and area of cultivation declined for the past years, mainly due to changes in dietary patterns favouring refined cereals such as rice, wheat, and maize. However, with the rising demand for nutrient-dense and functional foods, small millets are regaining importance as nutriceals, offering a sustainable and cost-effective alternative to major cereals (Bhat *et al.*, 2018; Bunkar, 2021).

Nutritionally, small millets are rich sources of dietary fiber, protein, essential amino acids, and micronutrients such as iron, zinc, calcium, and vitamins making them crucial for addressing micronutrient deficiencies and metabolic disorders. Their low glycemic index (GI) and gluten-free nature position them as ideal grains for diabetes management, cardiovascular health, and weight regulation (Sushree *et al.*, 2024). Moreover, they are rich in bioactive compounds, including phenolics, flavonoids, and tannins, which possess

antioxidant, anti-inflammatory, and antimicrobial activities. These compounds play a crucial role in boosting immune health and may help in the prevention of chronic diseases by reducing oxidative stress and inflammation. Furthermore, their prebiotic potential, attributed to their high fiber and polyphenol content, plays a key role in gut health and microbiota modulation. Recent advancements in nutritional genomics and biofortification strategies have further enhanced their nutrient density, increasing their potential in combating malnutrition and improving global food security.

Small millets also exhibit exceptional climate resilience, thriving in low-input, marginal environments with minimal water and soil fertility requirements. Their thickened cell walls and fibrous root systems contribute to drought tolerance and soil conservation, making them a valuable component of climate-smart agriculture (Bezbaruah and Singh, 2024). Their short life cycle makes them suitable for multiple cropping systems, further increasing their adaptability. Additionally, their extended shelf-life and natural pest resistance enhance their storage potential, making them viable for long-term food security and reducing post-harvest losses.

The six major small millet species include finger millet (*Eleusine coracana* (L.) Gaertn), kodo millet (*Paspalum scrobiculatum* L.), foxtail millet (*Setaria italica* (L.) P. Beauv.), proso millet (*Panicum miliaceum* L.), Japanese barnyard millet (*Echinochloa esculenta* (A. Braun.) H. Scholz.), little millet (*Panicum sumatrense* Roth. ex Roem. & Schult.). They are diverse in their centre of origins and nutritional

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composition providing health benefits (Table 1). This review highlights the nutritional status, prebiotic potential, biofortification approaches, and nutrigenomic advancements in small millets emphasizing their role in enhancing the living standards of mankind.

Table 1: Overview of small millets with their common names, origin, and health benefits. (Bhat *et al.*, 2019; Vetriventhan *et al.*, 2020; Hemamalini *et al.*, 2020)

Crop name	Synonym/Common name	Centre of origin	Health benefits
Finger millet (<i>Eleusine coracana</i> (L.) Gaertn)	bird's foot millet, ragi	Ethiopia and Uganda	Supports bone health and anemia
Kodo millet (<i>Paspalum scrobiculatum</i> L.)	cow grass, rice grass, ditch millet, Indian crown grass	India	Improves digestion and reduces the risk of anaemia
Foxtail millet (<i>Setaria italica</i> (L.) P. Beauv.)	Italian millet	China	Manages diabetes and aids in weight loss
Proso millet (<i>Panicum miliaceum</i> L.)	Common millet	China	Reduces inflammation and supports heart health
Barnyard millet (<i>Echinochloa esculenta</i> (A. Braun) H. Scholz)	Billion-dollar grass	Central Asia	Improves cardiovascular health
Little millet (<i>Panicum sumatrense</i> Roth ex Roem. & Schult.)	-	South-east Asia	Supports immune function and oxygen transport

2. Nutritional composition of small millets

Millets are a valuable source of macronutrients like carbohydrates, and proteins, micronutrients like iron, calcium, and magnesium,

bioactive compounds, and phytochemicals (Table 2). Even though, they have health benefits like alkaline-forming potential and polyunsaturated fatty acids (PUFA), they remain an under-appreciated food crop (Figure 1).

Table 2: Range of various macro and micronutrients in small millets

Nutrients	Finger millet	Kodo millet	Foxtail millet	Proso millet	Barnyard millet	Little millet	Reference
Macronutrients (g)							
Carbohydrates	72-72.6	65-66.6	60.9-63.2	63.8-70.4	55-65.5	66.6-67	Saleh <i>et al.</i> , 2013; Bhat <i>et al.</i> , 2019; Singh <i>et al.</i> , 2020
Protein	7.3-7.7	8.3-11	11.2-12.3	12.5	6.2-11	7.7-9.7	Saleh <i>et al.</i> , 2013; Bhat <i>et al.</i> , 2019; Sharma and Sandal, 2024
Fat	1.3-1.5	1.4-3.6	4-4.3	3.1-3.5	2.2-3.9	4.7-5.2	Bhat <i>et al.</i> , 2019
Micronutrients (mg/100 g)							
Vit B1	0.42	1.15	0.59	0.41	0.33	0.30	Saleh <i>et al.</i> , 2013
Vit B2	0.19	0.09	0.11	0.28	0.10	0.09	Saleh <i>et al.</i> , 2013; Singh <i>et al.</i> , 2020
Vit B3	1.1	2	3.2	4.5	4.2	3.2	Saleh <i>et al.</i> , 2013; Singh <i>et al.</i> , 2020
Vit E	22	-	31	-	-	-	Singh <i>et al.</i> , 2020
Calcium	344-350	27-35	31	8-14	11-22	17	Saleh <i>et al.</i> , 2013; Bhat <i>et al.</i> , 2019
Iron	3.9	1.7-12	2.8-5	2.9-10	15-18.6	6-9.3	Saleh <i>et al.</i> , 2013; Bhat <i>et al.</i> , 2019
Magnesium	137	147	81	153	82	133	Sanyal <i>et al.</i> , 2021

2.1 Macronutrients

2.1.1 Carbohydrates

Small millets are abundant in carbohydrates, accounting for 63-70%, primarily as starch, which makes them a staple energy source. Their carbohydrate profile includes free sugars such as glucose, sucrose,

fructose and maltose and structural components like cellulose and pentoses (Wankhede *et al.*, 1979). They have a low glycemic index due to their slow-digestible carbohydrates (Shah *et al.*, 2024). This makes them beneficial for managing diabetes and preventing spikes in blood sugar levels (Gupta *et al.*, 2023; Ansar *et al.*, 2024). Proso millet contains the highest carbohydrate levels among small millet

varieties (up to 75%), while finger millet provides a balance of starch and dietary fibre (Shankaramurthy *et al.*, 2019). Kodo millet and foxtail millet have higher fibre content than any other cereals and millets like rice, wheat, pearl millet, sorghum, and finger millet (Saleh *et al.*, 2013). Little millet is an exceptional source of dietary fibre ranging from 15.9-18.1% with varying soluble and insoluble fractions (Indhu *et al.*, 2024). This promotes better gut health, prevents excessive fat storage and facilitates sustained energy release (Hariprasanna, 2017). The starch in small millets is versatile and can be modified using physical, chemical, or enzymatic methods for broader applications in food formulations. This enhances their utility in processed food while retaining their nutritional benefits (Kaur *et al.*, 2023).

2.1.2 Proteins

Protein content ranges from 7-13% among small millets. Some proximate studies revealed that proso millet has the maximum protein content, accounting for 15.72%, followed by foxtail millet and barnyard millet (Hymavathi *et al.*, 2020). The foxtail cultivar RAU-8 is evidenced to have the highest seed protein among all millets (Bandyopadhyay *et al.*, 2017). In addition to their quantity, the protein quality in small millets is notable for containing essential amino acids such as leucine, isoleucine, and methionine. However, the lysine content tends to be low in comparison with major millets, limiting the overall biological value (48.3-56.5). The biological value can be enhanced by lysine fortification. The protein digestibility is high in small millets, ranging between 95-99. This range is reduced in the presence of anti-nutritional factors such as tannins and phytates. These inhibitors can be mitigated through germination, fermentation, and heat treatment, which improve bioavailability (Geervani and Eggum, 1989; Sharma and Gujral, 2019). Apart from antinutritional factors, abiotic stress like drought, salinity is also responsible for the reduction of soluble protein, protein digestibility and mineral uptake (Mirza and Marla, 2019; Kothai and Roselin Roobavathi, 2020; Tiwari *et al.*, 2022). Biopriming techniques using beneficial microbial isolates have been shown to improve nutrient uptake and stress tolerance in small millets (Kour *et al.*, 2020).

Compared to polished rice, dehulled minor millets have a much higher protein content, making them superior protein-based diets. In

comparison to wheat, proso millet has 54% greater amounts of essential amino acids (Saleh *et al.*, 2013; Karthick *et al.*, 2023). The functional properties of millet proteins like dough rheology, foaming, and emulsifying capacities, enhance their versatility in food processing (Sharma and Gujral, 2019).

2.1.3 Lipids and essential fatty acids

Small millets are a valuable source of lipids and essential fatty acids, contributing significantly to their nutritional and health-promoting properties. The lipid content varies from 15-8%. The lipids are primarily made of neutral lipids (70-72%), glycolipids (10-12%), and phospholipids (5-6%) in the finger millet (Mahadevappa and Raina, 1978). Additionally, their lipid composition in a study of little millet, kodo millet, and barnyard millet indicated the variation of free lipids (65-71%), bound lipids (21-26%), and structural lipids (7-8%), with little millet showing a high proportion of free lipids (Sridhar and Lakshminarayana, 1992).

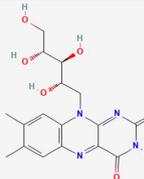
When compared to other millets, finger millet has a high composition of fatty acids like oleic (49-50%), linoleic (8-12%), and palmitic acid (25-30%) (Chandrashekar, 2010). These essential fatty acids are essential for maintaining cardiovascular health and reducing inflammation. The unsaturated nature of lipids enhances their antioxidant potential, making small millets a functional food choice for reducing oxidative stress, contributing to low glycemic index, and promoting overall metabolic health (Bora *et al.*, 2019). The conversion of little millets to RTC (ready-to-cook) flakes further improves their nutritional profile by lowering fat content and glycemic load due to the formation of amylose-lipid complex and partial gelatinization during steaming, respectively (Patil *et al.*, 2015).

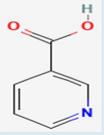
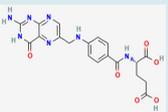
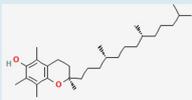
2.2 Micronutrients

2.2.1 Vitamins

The vitamin E and vitamin Bcomplex excluding vitamin B12 are predominant in small millets, contributing significantly to their nutritive profile and health benefits. The vitamins are mostly concentrated in the aleurone and pericarp layers of millets (Raju *et al.*, 2024) (Table 3).

Table 3: Role of vitamins in small millets

Vitamin	Predominant crop	Role	Reference
vitB1 (Thiamine) 	Foxtail millet, Proso millet	Energy metabolism and proper nerve function	Simwemba <i>et al.</i> , 1984; Bandyopadhyay <i>et al.</i> , 2017; Al-Khayri <i>et al.</i> , 2019
vitB2 (Riboflavin) 	Finger millet	Supports energy production and cellular function	Simwemba <i>et al.</i> , 1984

<p>vitB3 (Niacin)</p> 	<p>Foxtail millet, Proso millet, Little millet</p>	<p>Improves cholesterol levels and energy metabolism</p>	<p>Simwemba <i>et al.</i>, 1984; Al-Khayri <i>et al.</i>, 2019</p>
<p>vit-B9 (Folate)</p> 	<p>Finger millet, Kodo millet</p>	<p>DNA synthesis and prevent neural tube defects during pregnancy</p>	<p>Sharma and Sandal, 2024</p>
<p>vit-E (α-tocopherol)</p> 	<p>Proso millet, Finger millet, Foxtail millet</p>	<p>Antioxidant supports the immune system and protects cells from oxidative stress</p>	<p>Asharani <i>et al.</i>, 2010; Bandyo padhyay <i>et al.</i>, 2017; Raju <i>et al.</i>, 2024)</p>

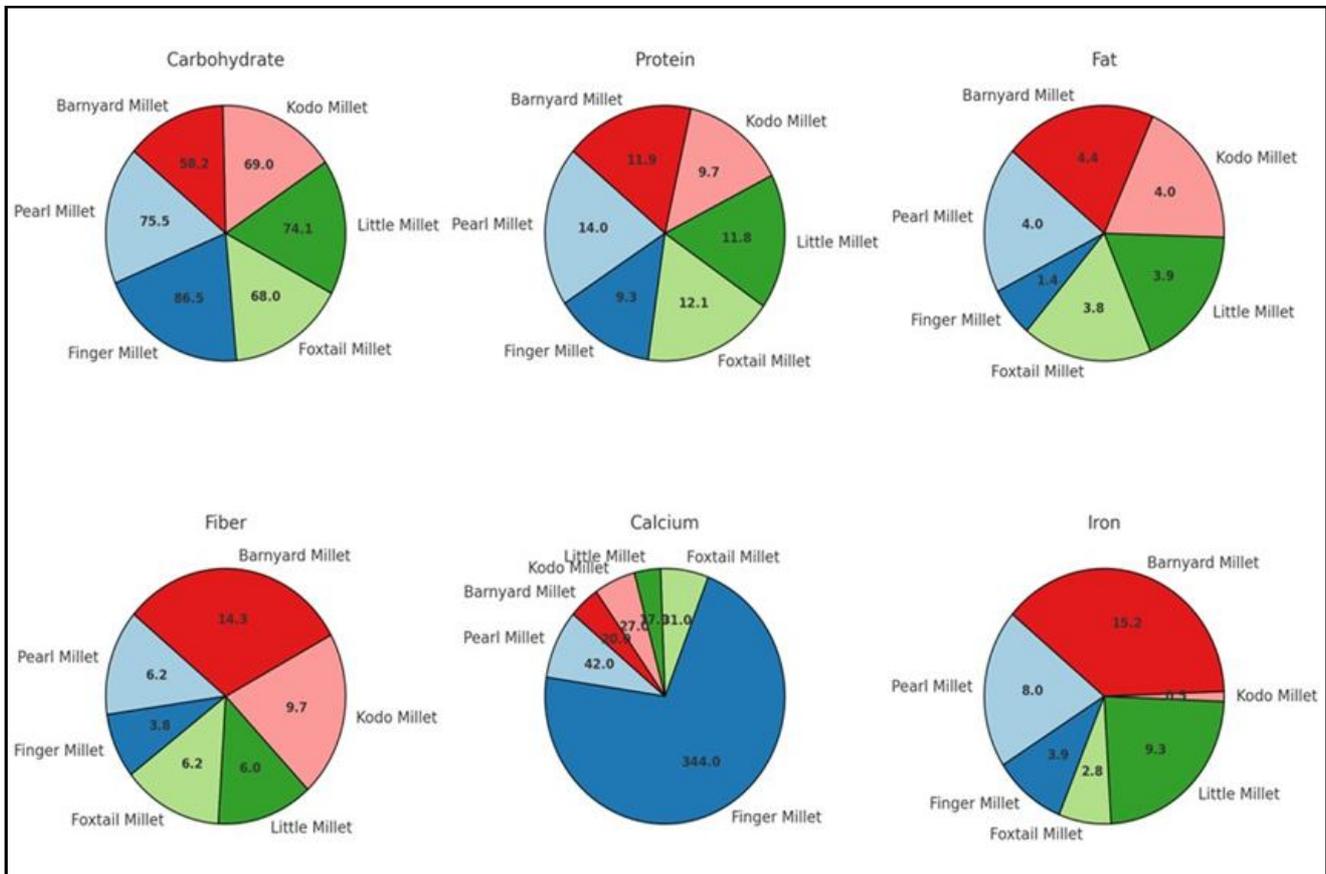


Figure 1: Nutrient distribution of macro and micronutrients across various small millets (Raju *et al.*, 2024).

2.2.2 Minerals

Small millets are nutritious grains known for their rich mineral contents. Finger millet is exceptionally rich in calcium, containing up to 3811.98 mg/kg, supporting bone health and helping to combat calcium deficiencies. Kodo millet is notable for its high iron content, with levels up to 206.5 mg/kg, making it ideal for addressing iron deficiency anemia (Hemamalini *et al.*, 2020). Little millet is a good

source of zinc, ranging from 2-8 mg/g, which plays a critical role in immune function and cellular repair (Manimozhi *et al.*, 2015). Additionally, small millets such as foxtail and barnyard millet provide magnesium, phosphorus, and potassium, supporting muscle function, energy metabolism, and cardiovascular health (Pasha *et al.*, 2018).

While small millets are rich in minerals, their bioavailability can be reduced by the presence of antinutritional components such as phytic

acid. Processing practices like soaking, fermentation, and germination can mitigate these inhibitors and enhance the absorption of minerals (Ravindran, 1991). In proso millet, oxalates and phytates are anti-nutritional factors, reduced through decortification and dehulling by 17-24% (Bhat *et al.*, 2019). Overall, the mineral rich profile of small millets makes them a valuable dietary option for improving nutrition and addressing micronutrient deficiencies, especially in regions facing food security challenges.

3. Bioactive compounds

The bioactive compounds such as flavonoids, phenolic acids, tannins, saponins, and lignans contribute to their functional and therapeutic properties. These are concentrated in the seed coat and offer nutritional benefits and a wide scale of health-promoting effects, such as antioxidant, anti-inflammatory, and enzyme-inhibitory activities, making them valuable for addressing chronic diseases.

3.1 Phenolic compounds

The phenolics exist in both soluble and bound forms, with the soluble fraction contributing significantly to 80% phenolic and flavonoid contents in cultivars of foxtail and little millets (Pradeep and Sreerama, 2018). Research on millets found that ferulic and p-coumaric acids are more in the soluble counterparts. Kodo millet possesses the highest and proso millet with the least contents of phenolics (Chandrasekara and Shahidi, 2010). The dark coloured finger millet varieties had higher antioxidant properties and phenolic contents in contrast with the lighter ones (Xiang *et al.*, 2019).

Hydroxycinnamoyl derivatives and feruloylated flavonoids found in foxtail millet enhance its resistance to environmental stress and provide robust antioxidant properties. These metabolites are observed to follow dominant inheritance patterns, making them valuable for hybrid breeding programs (Li *et al.*, 2018). Phenolic acids like gallic acid and syringic acid in small millets have demonstrated anti-inflammatory and anticarcinogenic effects (Kaur *et al.*, 2019). These compounds exhibit significant radical scavenging and metal-chelating activities (Chandrasekara and Shahidi, 2010). Phenolics also inhibit key digestive enzymes such as α -amylase and α -glucosidase, thereby delaying glucose release and demonstrating its potential for managing diabetes (Pradeep and Sreerama, 2018).

Despite the high concentration of bioactive compounds in millets, their bioavailability can be limited due to factors like complex binding with proteins and antinutritional factors. However, processing techniques such as soaking and fermentation improve the bioavailability of polyphenols and other metabolites (Tharifkhan *et al.*, 2021).

3.2 Carotenoids

These are the natural isoprenoid compounds. Lutein and zeaxanthin are the predominant carotenoids found in millets like foxtail millet, which contribute to their characteristic yellow pigmentation. Studies reveal that lutein and zeaxanthin concentrations range from 12.98-22.55 mg/kg and 6.18-13.99 mg/kg, respectively. The carotenoids present in small millets are generally lower than those in fruits and vegetables, these compounds are stable and bioaccessible unless processed or cooked under high pressures (Shen *et al.*, 2015).

The variation in the expression of carotenoid biosynthetic genes, such as SiPSY1 and SiCCD1, significantly affects the carotenoid accumulation in yellow and white foxtail millet varieties. Yellow varieties show higher carotenoid levels due to the upregulation of biosynthetic genes (Zhang *et al.*, 2019; He *et al.*, 2022). Small millets are a moderate source of carotenoids, their potential as a functional food ingredient can be further enhanced through optimized cooking and processing techniques.

3.3 Tannins

They are potent antioxidants and can also act as antinutritional factors by binding with proteins and minerals, thus reducing their bioavailability. They are mostly associated with the glutelin protein fraction, which affects protein digestibility. They are predominantly located in the seed coat of the small millet grains. For instance, finger millet varieties with dark-colored seeds generally exhibit higher tannin content compared to lighter-colored ones, contributing to stronger antioxidant activity (Siwela *et al.*, 2007).

Dehulling and other processing techniques like germination, and fermentation are effective in reducing tannin levels. Boiling, roasting, and controlled fermentation were found effective in lowering the tannin levels in finger millet. Germination has also been shown to decrease tannins while simultaneously mounting the bioavailability of minerals like iron and zinc (Ramachandra *et al.*, 1977, Singh *et al.*, 2017). Processing techniques play a crucial role in enhancing the overall nutritional quality of small millet-based foods.

3.4 Lignans

These are the group of phytoestrogenic compounds found in small millets. The uptake of plant lignans is partially converted to enterolignans by gut microbiota influencing metabolic pathways associated with the prevention of chronic diseases (Durazzo *et al.*, 2013). Studies indicate that millets contain significant amounts of lignans, including syringaresinol and 7-hydroxymatairesinol, which contribute to their health benefits. These compounds act as immune modulators and detoxifying agents, helping to combat oxidative stress and inflammation-related disorders (Smeds *et al.*, 2007). The health benefits of lignans extend beyond antioxidant properties. They have been linked to reduced risks of hormone-related cancers, cardiovascular diseases, and metabolic disorders (Kavitha *et al.*, 2024). However, processing methods such as milling and refining can reduce lignan content, as these compounds are primarily concentrated in the bran layers of the grain (Tripathi *et al.*, 2021).

3.5 Saponins

They belong to the group of naturally occurring glycosides in small millets, contributing to nutritional and functional properties (Bomford *et al.*, 1989). They bind to bile acids, preventing cholesterol absorption. Besides them, they are also known for their anti-inflammatory and anticancer properties (Dey *et al.*, 2022). Studies on barnyard millet and proso millet indicate moderate levels of saponins (Pujari *et al.*, 2022). Finger millet also contains these compounds but is lower when compared with pearl millet (Sibi *et al.*, 2024). However, processing methods such as popping can reduce the saponin content, improving palatability and digestibility (Kumari *et al.*, 2025).

4. Prebiotic potential of small millets

The recognition of small millets as functional foods due to the presence of high dietary fiber content and polyphenols highlights their prebiotic potential. The non-digestible constituents of food are denoted as prebiotics, these selectively promote the growth of beneficial gut microbiota, particularly *Lactobacillus* and *Saccharomyces* species, improving gut health and overall metabolic functions (Soni *et al.*, 2024). Studies on fermentation of finger and kodo millet using *Saccharomyces*, *Campanilactobacillus*, *Bifidobacterium*, and *Hanseniaspora* revealed an increase in phenols and minerals like calcium and iron (Balli *et al.*, 2023). They significantly enhance fiber solubility, making fermentation-based foods effective carriers for gut microbiota modulation. The preparation of soups using kodo, barnyard, and foxtail millet attained ideal prebiotic scores (Arya *et al.*, 2021). Since the prebiotic studies were limited to pearl millet and finger millet, there is ample opportunity to uncover their ability in other small millets (Palaniappan *et al.*, 2017; Mondal *et al.*, 2023).

5. Nutritional genomics of small millets

The information on the genomics of a crop is the prerequisite for characterization and their role in crop improvement (Varshney *et al.*, 2011) (Table 4). Recent advances in genome sequencing and omic technologies have provided insights into the genetic basis of nutrient accumulation and stress tolerance, aiding in genome-assisted breeding programs (Kudapa *et al.*, 2023). Firstly, the identification of foxtail millet assists as a model crop for C_4 species because of its small genome size ranging about 423-510 Mb. It is the first crop in which the whole genome was sequenced among millets (Vetriventhan *et al.*, 2020). The highest cross-transferability is seen for ILP markers of foxtail millet (94.1 %), followed by SSR markers of foxtail and finger millet (Renganathan *et al.*, 2020).

The omic studies revealed 145 CaMK1, 125 CaMK2 proteins, and 29 CAX1, 3 TPC1 genes are found homology with calcium accumulation and transport (Hittalmani *et al.*, 2017). Proteomic studies on foxtail millet under drought conditions revealed 2474 differentially expressed proteins performing varied functions to maintain homeostasis by fatty acid, amino acid, hormone metabolisms, and modifications in the cell wall (Pan *et al.*, 2018). Similar studies in proso millet using 2-D gel electrophoresis and mass fingerprinting detected 1152 protein spots, most of them related to the metabolism of starch and polysaccharides (Roy *et al.*, 2017). Metabolite reports in proso millet identified 43 primary metabolites and 5 phenolic compounds (Kim *et al.*, 2013). Transcriptomic analysis for insights into higher iron content at different stages found genes linked to important processes like transporting metals, building proteins, and responding to plant growth hormones (Padhiyar *et al.*, 2024). Works to identify the orthologous gene associated with enriching nutrients by metal uptake and drought response have been reported (Chandel *et al.*, 2017; Sushmitha, 2018). The comparative genomics with major cereals helped in the identification of key quantitative trait loci (QTL) and genes governing protein quality in finger millet (Vinoth and Ravindhran, 2017).

The metagenomic studies have shown rhizosphere microbiome capabilities in the improvement of plant growth in semi-arid, dry conditions. Actinobacteria and proteobacteria perform functions like carbon fixation, nitrogen, phosphorus, sulfur, iron, aromatic compound metabolism, stress response, and defense (Prabha *et al.*, 2019). This shows the scope of research in this area for nutrient-specific crop improvement. Due to the limited studies in multi-omics of the small millet directed towards less scope in its improvement.

Table 4: Genomics and omic insights of small millets

Crop name	Genome size	Identified QTLs	Molecular markers used	Advanced omic studies applied	Reference
Finger millet	1196-1500 Mb (Draft genome available)	Blast resistance, Phosphorus efficiency, and biochemical traits	SSR, SNP, AFLP, DArT	Transcriptomics, proteomics, metabolomics, epigenomics	Hittalmani <i>et al.</i> , 2017; Ramakrishnan <i>et al.</i> , 2017; Hatakeyama <i>et al.</i> , 2018
Kodo millet	1900 Mb (No complete genome available)	Nutrient accumulation, Drought and salinity tolerance	SSR, SNP	Metabolomics, genome-wide association studies (GWAS), transcriptomics	Banshidhar <i>et al.</i> , 2023; Shukla <i>et al.</i> , 2024
Foxtail millet	401-510 Mb (Fully sequenced)	Agronomic traits, abiotic stress tolerance, nutrient uptake, and transport	SSR, SNP, AFLP, RFLP	Whole-genome sequencing, epigenomics, comparative genomics	Bennetzen <i>et al.</i> , 2012; Renganathan <i>et al.</i> , 2022; Krishna <i>et al.</i> , 2022; Kumar <i>et al.</i> , 2024
Proso millet	837-923 Mb (Draft genome available)	Phenotypic traits, cold stress	SSR, SNP, RAPD, ISSR	RNA sequencing, metabolomics, proteomics	Rajasekaran and Francis, 2021; Kumar <i>et al.</i> , 2024
Barnyard millet	1.27 Gb (No complete genome available)	Waxy traits	SNP, ISSR, SSR	Proteomics, comparative genomics, QTL mapping	Renganathan <i>et al.</i> , 2022
Little millet	Unknown (No complete genome available)	-	SSR, SNP, RAPD	Functional genomics, metabolomics	Ratnam <i>et al.</i> , 2025

6. Biofortification in small millets

The long-term strategy and cost-effective process to enhance the micronutrient density of food crops is achieved through biofortification. The further genetic improvement of nutrient-rich crops towards increasing their dietary value, especially vitamins and minerals helps in the eradication of hidden hunger and malnutrition. This could be achieved through conventional breeding approaches and genomic interventions (Kudapa *et al.*, 2023) (Figure 2).

Genomic tools such as GWAS (Genome-Wide Association Mapping) and QTL mapping help to identify genetic markers linked to high micronutrient traits in small millets (Vellaichamy *et al.*, 2023).

Agronomic and microbial biofortification techniques can be employed in small millets which enhances the soil nutrient mobility and microbiota, thereby improving the availability of nutrients (Kadapa *et al.*, 2023; Chaudhary, 2024). Most of the works are reported in pearl millet. For instance, genetic variability in germplasm has been explored to identify a superior line rich in iron, zinc, and calcium (Govindaraj *et al.*, 2020). Further, iron-biofortified pearl millet varieties (ICTP 8203 Fe-10-2) have been developed (Vinoth and Ravindhran, 2019). Future research should focus on germplasm exploration for nutritious lines, and implementing genome editing tools like CRISPR-Cas9 for biofortification in small millets.

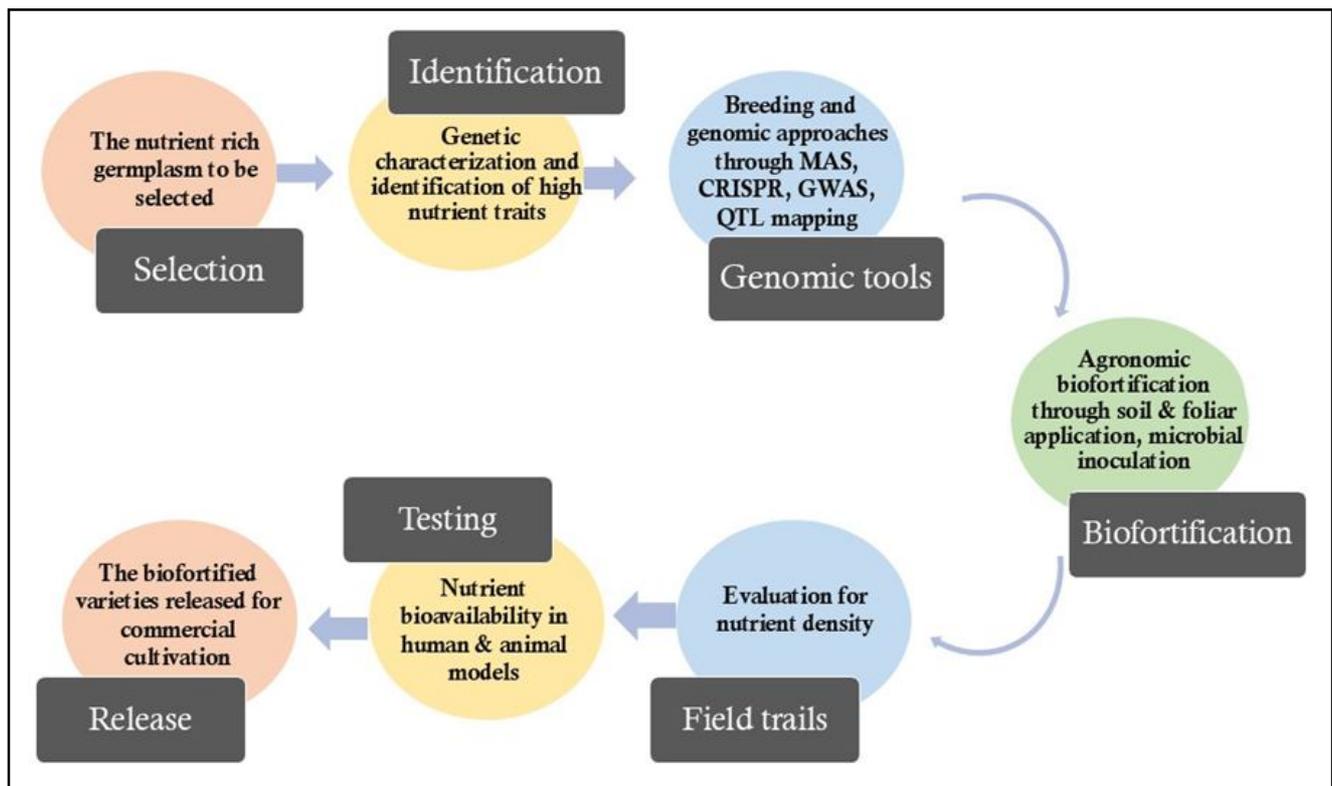


Figure 2: Procedure for nutritional improvement through biofortification (Vinoth and Ravindhran, 2019; Govindaraj *et al.*, 2020; Kudapa *et al.*, 2023).

7. Conclusion

Small millets stand out as nutritional powerhouses, offering a rich blend of fiber, protein, essential micronutrients, and bioactive compounds, making them invaluable in addressing malnutrition and lifestyle disorders. Their low glycemic index and gluten-free nature make them ideal for diabetes and metabolic health, while bioactive compounds such as polyphenols, flavonoids, and tannins provide antioxidant, anti-inflammatory, and cardioprotective benefits. Enhancing their nutrient bioavailability through germination, fermentation, and innovative processing can further elevate their health potential. Looking ahead, biofortification and genetic advancements can boost their nutritional density while reducing antinutrient levels. Nutritional genomics and genome-assisted breeding hold promise in improving their nutrient uptake and bioavailability. Despite their immense nutritional and agronomic potential, small

millets remain under-researched compared to major cereals. Key gaps include limited genomic resources, low bioavailability of certain nutrients due to antinutritional factors, and incomplete understanding of their endophytic interactions. Additionally, prebiotic potential linked to fiber and polyphenols is well-recognized, but research remains heavily focused on pearl millet, highlighting a significant limitation on small millets. Enhancing nutrient density through genetic and breeding interventions, particularly for iron, zinc, and calcium, is crucial for improving the dietary value of small millets. Exploring their functional food applications, and optimizing processing techniques to retain bioactive compounds can unlock new possibilities. As resilient, climate-smart crops, small millets present a sustainable solution for food security. Advancing fortified, ready-to-eat millet-based products and integrating traditional understandings with cutting-edge science will solidify their global recognition as a health-promoting and nutritionally superior grain of the future.

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Conflict of interest

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

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