

Millets as Nutraceuticals Compounds, Therapeutic Potential and Opportunities for Advanced Delivery Systems

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Abstract

Millets are climate-resilient cereal crops that are increasingly important for food security, nutrition, sustainable agriculture and public health. They are rich in carbohydrates, proteins, dietary fibre, minerals and several bioactive compounds, including phenolic compounds. These characteristics make millets important cereals for functional foods and nutraceutical research. Among Indian millets, *Pennisetum glaucum* (Pearl Millet), *Eleusine coracana* (Finger Millet) and *Sorghum bicolor* (Sorghum) are particularly important because of their nutritional value and adaptability to difficult growing climatic condition.

This review examines the nutritional characteristics, bioactive compounds, potential health benefits and pharmaceutical relevance of millets. It also discusses advanced delivery systems for developing millet-based nutraceutical products. Although millets have shown antioxidant, metabolic and gastrointestinal health potential, the presence of a bioactive compound in a grain does not by itself prove therapeutic efficacy. Factors such as dose, stability, bioavailability, processing and clinical validation are important before health claims can be established.

A systematic pathway from crop selection and bioactive characterization to formulation, preclinical testing and clinical validation could help convert millet-derived compounds into standardized and evidence-based functional foods and nutraceutical products.

Keywords: millets; nutraceuticals; phenolic compounds; dietary fibre; antioxidant activity; advanced delivery system

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1. Introduction

Millets have gained renewed attention because of their nutritional value, climate resilience and potential contribution to sustainable agriculture. They have been cultivated in India for centuries and are well adapted to low-rainfall areas, marginal soils and challenging climatic conditions.

Millets hold deep historical, cultural, and agricultural significance, tracing their roots back over 5,000 years. Archaeological evidence from sites such as Harappan, Hallur (Karnataka), and Atranjikhhera (Uttar Pradesh) suggest that millets like foxtail (*Setaria italica*), little millet (*Panicum sumatrense*), and barnyard millet (*Echinochloa frumentacea*) were among the earliest domesticated

crops in the Indian subcontinent (Veerabhadran et al, 2023). India is one of the major millet-producing countries, with important crops including sorghum, pearl millet, finger millet, foxtail millet, little millet, barnyard millet, proso millet, kodo millet and brown-top millet etc.

Millets contain carbohydrates, proteins, dietary fibre, minerals, vitamins and several phytochemicals. Their nutritional composition has attracted increasing interest in the areas of functional foods and nutraceuticals (Longvah *et al.*, 2017; FAO, 2021). Some millet varieties are also good sources of phenolic compounds and other

antioxidants that may contribute to their functional properties (Chandrasekara & Shahidi, 2011).

Pearl millet, finger millet and sorghum are particularly important due to nutritional perspective and these millets are important and more adaptable in the arid and semi-arid areas available in India. Pearl millet is known for its protein, iron, magnesium and zinc content, while sorghum contains dietary fibre and phenolic compounds. Finger millet is particularly well known for its high calcium content and its dietary fibre and polyphenol content (Devi *et al.*, 2014). The increasing interest in millets provides an opportunity to explore their use not only as traditional foods but also as sources of standardized nutraceutical ingredients (Nithiyanantham *et al.*, 2019). However, it is important to distinguish between nutritional benefits and therapeutic effects. The presence of potentially beneficial compounds does not automatically mean that a millet or millet extract can be considered a therapeutic product. Appropriate chemical characterization, bioavailability studies, safety assessment and clinical validation are required.

This review therefore examines millets from a functional-food and nutraceutical perspective, with particular emphasis on bioactive compounds, health-related potential, processing, standardization and advanced delivery systems.

2. Millets as Food and Nutraceuticals Perspective

Millets are increasingly recognized as functional foods because they provide essential nutrients, dietary fibre and bioactive compounds that may support human health. Among the major millets, pearl millet (*Pennisetum glaucum*), finger millet (*Eleusine coracana*) and sorghum (*Sorghum bicolor*) have significant nutritional and functional value.

2.1 Pearl Millet

Pearl millet is a good source of protein (Prolamins and glutelins (Chandna, & Matta, 1990)), iron, magnesium, zinc and dietary fibre, making it useful for improving dietary quality (Hassan *et al.*, 2021). It also contains B-complex vitamins (Singh *et al.*, 2023). Approximately 10–12% protein and 1.2–1.5 g dietary fibre per 100 g have been reported in commonly cited nutritional data (Nibhoria *et al.*, 2024). Its combination of protein, fibre and micronutrients makes pearl millet useful for developing nutrient-dense functional foods. The presence of phenolic compounds also provides an opportunity for further investigation of its antioxidant properties. Pearl Millet fibre has a high water-holding capacity, which may support

digestion and increase satiety. The fibre also shows cholesterol and glucose-absorption capacity, suggesting a potential role in maintaining healthy blood glucose and cholesterol levels. Its prebiotic properties can support beneficial gut microorganisms and contribute to better intestinal health. In addition, pearl millet fibre exhibits strong antioxidant activity, helping to neutralize harmful free radicals (Manju *et al.*, 2025). The major phenolic acids reported in pearl millet include ferulic acid, p-coumaric acid, caffeic acid, gallic acid, vanillic acid, syringic acid, protocatechuic acid, salicylic acid, and sinapic acid. It also contains flavonoid compounds such as quercetin, kaempferol, rutin, catechin, and epicatechin. Among these, ferulic acid and p-coumaric acid are important phenolic acids and are commonly present in bound forms associated with the grain cell wall (Mawouma *et al.*, 2022).

2.2 Finger Millet

Finger millet (ragi) contains approximately 7–8% protein and around 3.6 g dietary fibre per 100 g. It is particularly rich in calcium and also provides iron, phosphorus and B-complex vitamins (ICAR-IIMR, 2024). Finger millet polyphenols and dietary fibre have received considerable research attention. These components may contribute to antioxidant activity and other health-related effects (Devi *et al.*, 2014). Finger millet is particularly rich in calcium and also contains dietary fibre and polyphenols, which contribute to its potential benefits for bone health and antioxidant activity (Maharajan *et al.*, 2021).

2.3 Sorghum

Sorghum (jowar) contains approximately 9–11% protein and around 1.5 g dietary fibre per 100 g. It also provides iron, phosphorus, potassium and B-complex vitamins (ICAR-IIMR, 2024). Sorghum several varieties contain phenolic compounds and other phytochemicals. These compounds may contribute to antioxidant activity and other biological properties (Chandrasekara & Shahidi, 2011). It contains dietary fibre and phenolic compounds that may contribute to antioxidant activity and metabolic health (Espitia-Hernández *et al.*, 2022).

These millets can be incorporated into traditional foods, breakfast cereals, bakery products, nutritional supplements and other functional-food formulations shown in the Table 1.

Table 1. Proximate nutrient composition and nutritive value

V a r i e t y	C a r b o h y d r a t e (g)	P r o t e i n (g)	F a t (g)	A s h (g)	F i b r (g)	C a (m g)	F e (m g)	Z n (m g)	T h i a m i n (m g)	R i b o f l a v i n (m g)	N i a c i n (m g)	E n e r g y (k c a l)
S o r g h u m	71	10.4	3.1	1.8	2.0	2.5	5.4	3.1	0.38	0.15	4.3	3.29
F i n g e r m i l l e t	59-75	6.9-10.9	1.5	2.6	1.5	3.5	3.9	3.1	0.42	0.19	1.1	3.36
P e a r l m i l l e t	67-72	11.0	5.1	2.2	1.3	4.2	1.0	3.2	0.38	0.21	2.8	3.63

Note: Nutrient values are expressed per 100 g of dry matter (g/100 g or mg/100 g, as applicable (Kumar et al., 2021)).

3. Bioactive Compounds in Selected Millets

Pearl millet (*Pennisetum glaucum*), finger millet (*Eleusine coracana*), and sorghum (*Sorghum bicolor*) are nutritionally important cereals rich in proteins, dietary fibre, and phenolic compounds. Their major protein fractions include albumins, globulins, prolamins, and glutelins, with pennisetins in pearl millet and kafirins in sorghum. Finger millet is notable for its essential amino acids, including methionine. Dietary fibre in these millets includes cellulose, hemicellulose, arabinoxylans, β -glucans, lignin, and soluble and insoluble fibre. They also contain important phenolic compounds, such as ferulic acid, p-coumaric acid, gallic acid, caffeic acid, and syringic acid. Finger millet contains flavonoids such as quercetin, catechin, and luteolin,

while sorghum is notable for 3-deoxyanthocyanidins and condensed tannins. These bioactive compounds may contribute to antioxidant activity and other health benefits are summarized in below Table 2.

Table 2: Proteins, dietary fibre and phenolic compounds

Mille t	Maj or prot eins / prot ein fract ions	Major dietary fibre compo nents	Important phenolic compounds / groups	Refe renc es
Pearl millet (<i>Penn isetu m glauc um</i>)	Albu mins, glob ulins, prola mins and glute lins; prola mins inclu de penni setin s	Cellulo se, hemicel lulose, arabino xylans, β - glucans, lignin, and soluble/ insolubl e dietary fibre	Ferulic acid, p-coumaric acid, caffeic acid, gallic acid, syringic acid, quinic acid, flavonoids and tannins	Hass an <i>et al.</i> (202 1); Triki <i>et al.</i> (202 2); Kum ar <i>et al.</i> (202 1)
Finge r millet (<i>Eleu sine corac ana</i>)	Albu mins, glob ulins, prola mins and glute lins; conta ins relati vely impo rtant level s of essen tial amin o acids inclu ding meth ionin e	Cellulo se, hemicel lulose, arabino xylans, β - glucans, pectin and lignin; both soluble and insolubl e fraction s	Ferulic acid, p-coumaric acid, protocatech uic acid, gallic acid, syringic acid, p- hydroxyben zoic acid, quercetin, catechin, epicatechin, kaempferol, luteolin and apigenin; tannins and proanthocya nidins	Devi <i>et al.</i> (201 4); Chan dra <i>et al.</i> (201 6); Udeh <i>et al.</i> (201 7)

Sorghum (<i>Sorghum bicolor</i>)	Kafirins (major proteins), albumins, globulins and glutelins	Cellulose, hemicellulose, arabinoxylans, β -glucans and lignin, including soluble and insoluble dietary fibre	Ferulic acid, gallic acid, vanillic acid, <i>p</i> -coumaric acid, caffeic acid, luteolin, apigenin, 3-deoxyanthocyanidins, flavonoids and condensed tannins/proanthocyanidins	Xiong <i>et al.</i> (2019); Wu <i>et al.</i> (2021); Liu <i>et al.</i> (2023)
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4. Therapeutic potential of selected Millets

Pearl millet (*Pennisetum glaucum*), finger millet (*Eleusine coracana*), and sorghum (*Sorghum bicolor*) contain valuable nutrients and bioactive compounds that support human health (Espitia-Hernández *et al.*, 2022). Pearl millet is rich in dietary fibre, phenolic acids, flavonoids, magnesium, and iron, contributing to antioxidant activity, digestive health, cholesterol management, and blood-glucose regulation (Chauhan *et al.*, 2018). Finger millet provides dietary fibre, calcium, polyphenols, tannins, flavonoids, and essential amino acids, offering potential benefits for blood-glucose control, bone health, satiety, and cholesterol reduction (Abioye *et al.*, 2022). Sorghum contains polyphenols, phenolic acids, flavonoids, tannins, anthocyanins, and dietary fibre, which may support antioxidant and anti-inflammatory activity, cardiovascular health, and healthy glucose and lipid metabolism (Khalid *et al.*, 2022). These properties make the three millets promising ingredients for functional foods and nutraceutical development.

Table 3: Major Bioactive and Nutritional Components of Millet

Millet	Important bioactive/nutritional components	Major therapeutic potential
Pearl millet (<i>Pennisetum glaucum</i>)	Dietary fibre, phenolic acids (ferulic, <i>p</i> -coumaric, caffeic acids), flavonoids, magnesium, iron	Antioxidant activity, blood-glucose regulation, cholesterol management, improved digestive health,

		prebiotic effects, cardiovascular health and potential anti-inflammatory activity
Finger millet (<i>Eleusine coracana</i>)	Dietary fibre, calcium, polyphenols, tannins, flavonoids, essential amino acids	Antidiabetic potential, antioxidant activity, bone-health support, cholesterol reduction, improved satiety and digestive health
Sorghum (<i>Sorghum bicolor</i>)	Polyphenols, phenolic acids, flavonoids, tannins, anthocyanins, dietary fibre	Antioxidant, anti-inflammatory, antidiabetic and cardiovascular protective potential; may support gut health and help regulate blood glucose and lipid metabolism

5. Opportunities for Advanced Delivery Systems

Millets such as pearl millet, finger millet, and sorghum offer promising opportunities for developing advanced delivery systems for bioactive compounds and nutraceutical ingredients (Sundaresan *et al.*, 2026). Their dietary fibre, proteins, starch, and phenolic compounds can be used to develop functional food formulations, microencapsulation systems, nanoemulsions, liposomes, polymeric nanoparticles, solid lipid nanoparticles, phytosomes, controlled-release oral formulations and biodegradable edible films (Kyriakoudi *et al.*, 2021). These technologies may improve the stability, solubility, bioavailability, and controlled release of sensitive bioactive compounds, including phenolic acids, flavonoids, vitamins, and minerals.

Millet-based starch and proteins can also serve as natural carriers for probiotics, prebiotics, and plant-

derived antioxidants (Pawale *et al.*, 2025). Furthermore, encapsulation can help protect bioactive compounds during food processing, storage, and digestion (Zabot *et al.*, 2022). Such innovations create opportunities for developing functional beverages, fortified foods, dietary supplements, and targeted nutraceutical products while promoting sustainable utilisation of millet resources.

These systems should not be considered automatically superior to conventional formulations. Their suitability must be assessed through studies of particle size, encapsulation efficiency, loading capacity, stability, release behaviour, gastrointestinal performance, toxicity and scalability (Umapathy *et al.*, 2024).

Table 3: Advanced Delivery Systems for Millet-Based Bioactive Compounds

Advanced delivery system	Millet components used	Potential applications and benefits
Functional food formulations	Dietary fibre, proteins, starch, phenolic compounds	Development of nutrient-rich foods supporting digestive health and overall nutrition (Saleh <i>et al.</i> , 2013)
Microencapsulation	Phenolic compounds, proteins, starch	Protects sensitive bioactive compounds from degradation and improves stability during processing and storage (Sandhya <i>et al.</i> , 2025)
Nanoemulsions	Phenolic compounds and other hydrophobic bioactives	Improves dispersion and may enhance the bioavailability of poorly water-soluble compounds

		(Roustaaazad <i>et al.</i> , 2025)
Liposomes	Phenolic compounds and other bioactive ingredients	Encapsulates hydrophilic and lipophilic compounds and may improve their stability (Chandrasekara <i>et al.</i> , 2011)
Polymeric nanoparticles	Millet starch, proteins, phenolic compounds	Enables protection and potentially controlled delivery of bioactive ingredients (Chavan <i>et al.</i> , 2024)
Solid lipid nanoparticles	Millet-derived bioactives incorporated into lipid carriers	May improve the stability and delivery of poorly water-soluble bioactive compounds (Ashfaq <i>et al.</i> , 2023)
Phytosomes	Millet phenolic compounds and flavonoids	Complexes plant bioactives with phospholipids to potentially improve absorption (Shah <i>et al.</i> , 2021)
Controlled-release oral formulations	Dietary fibre, starch, proteins and encapsulated bioactives	May regulate the release of nutrients and bioactive compounds during digestion (Jhan <i>et al.</i> , 2022)

Biodegradable edible films	Millet starch, proteins and dietary fibre	Develops sustainable food packaging that may help protect food quality (Shaikh <i>et al.</i> , 2019)
Probiotic and prebiotic delivery systems	Dietary fibre, resistant starch and millet proteins	Supports probiotic protection and delivery, with potential benefits for gut health (Sandhya <i>et al.</i> , 2025)

6. Conclusion

Millet is not only climate-resilient cereal crops but also valuable sources of nutrients, dietary fibre and bioactive compounds with potential applications in functional foods and nutraceuticals. Pearl millet, sorghum and finger millet provide important proteins, minerals, fibre and phytochemicals, although their composition varies according to species, variety, cultivation and processing.

The available evidence supports further investigation of millet-derived ingredients for antioxidant, metabolic and gastrointestinal applications. However, nutritional value should not be confused with proven therapeutic efficacy. Future development should focus on raw-material authentication, bioactive characterization, standardization, bioaccessibility, formulation, safety and clinical validation.

A coordinated approach connecting sustainable millet production with food processing, pharmaceutical formulation and evidence-based health research could help transform millet-derived components into high-quality functional foods and nutraceutical products. Such an approach could also contribute to sustainable agriculture, rural livelihoods, nutrition security and the development of innovative health products in India.

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