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Review Article

Assessment of nutritional components and nutraceutical benefits of millets: An integrative review

Narendra Kumar Ahirwar[1,*], Ravindra Singh [1]

[1] *Dept. of Biology Science, Mahatma Gandhi Chitrakoot Gramodaya Vishwavidyalaya, Chitrakoot, Satna, Madhya Pradesh, India*

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ABSTRACT

Despite being a lesser-known group of cereal grains, millets boast a rich nutritional and nutraceutical profile. Often mischaracterized as sustenance for the underprivileged, millets provide an impressive array of nutrients, rivalling many mainstream cereals. Notably, they offer substantial amounts of energy, carbohydrates, and protein, and even surpass other cereals in their content of fats, calcium, iron, dietary fiber, and Vitamin E, including both tocopherols and tocotrienols. Their remarkable phytochemical composition, which includes phenolic acids, flavonoids, catechins, phytic acid, and phytosterols, has captured the attention of researchers. It's been documented that the dietary fiber and phenolic compounds present in millets are instrumental in mitigating various health ailments, including diabetes, cardiovascular issues, and cataract development. These phytochemicals are also recognized for their antioxidant and antimicrobial attributes.

1. Introduction

Millets, which are hardy small-seeded grasses, thrive in dry regions, prospering as rain-fed crops even in soils with limited fertility and moisture. Globally, they contribute to less than 1% of total cereal production and make up 3% of coarse cereal output. African nations dominate millet cultivation, representing 59% of the global cultivation area and producing 55% of the world's supply. Asian nations follow closely, covering 38% of the cultivation area and contributing 42% to global yields. According to FAOSTAT data, the worldwide production of millets stood at 30.35 million tonnes in 2016. Of this, India's contribution was approximately 10 million tons, with a subset of small millet production at 467 thousand tons. In many developing countries, millets are predominantly consumed as a staple food due to their high nutritive value and energy content. Furthermore, in recent times, they've become a significant ingredient in various processed foods.

The primary types of millets are sorghum and pearl millet. Within the category of small millets, there are several distinct varieties: finger millet (Eleusine coracana), foxtail millet (Setaria italica), proso or white millet (Panicum miliaceum), barnyard millet (Echinochloa spp.), kodo millet (Paspalum scrobiculatum), and little millet (Panicum sumatrense).

2. Nutrient Profile of Millets

Millets offer a wealth of essential nutrients, encompassing carbohydrates, proteins, dietary fiber, minerals, and vitamins. While their protein content aligns closely with other cereals, they tend to have fewer carbohydrates. The fat levels in common millet, foxtail millet, and barnyard millet are notably elevated, which can affect their storage longevity. The substantial ash content in millets indicates

* *Corresponding author*.
E-mail address: narendra87.ahirwar@gmail.com (N. K. Ahirwar).

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a pronounced presence of inorganic substances. Notably, finger millet stands out as a premier source of calcium.

2.1. Carbohydrates

Millet carbohydrates in processed grains are characterized by free sugars (2-3%), non-starchy polysaccharides (15-20%), and a predominant starch component (60-75%). The free sugars largely include glucose, fructose, and sucrose. Non-starchy polysaccharides, recognized as dietary fibers, consist of cellulose, hemicellulose, and materials resembling pectin. Millets notably lack flatulence-inducing oligosaccharides like arabinose and stachyose. While trace amounts of β-glucans and substances similar to lignin exist, about 90% of the total dietary fiber is insoluble, mainly derived from the aleurone layer and the kernel's cell wall. The starch in millets, comprising both amylose and amylopectin, mirrors the 25:75 ratio found in other cereals. Millets have a reputation for their high amylose content, with some starch-rich varieties grown especially in China. The starch granules are densely packed within the cellular structure, leading to a predominantly vitreous endosperm. Research by scholars such as Subramanian and Jambunathan, Murty et al., and others indicates that pearl millet contains the highest total sugars (2.16-2.78 g/100 g), trailed by finger millet (0.59-0.69) and foxtail millet (0.46). Pearl millet also leads in content of raffinose and stachyose. Sucrose emerges as the dominant sugar in finger millet (0.20-0.24 g/100 g), foxtail millet (0.15), and proso millet (0.66).[1] The nutrient composition is shown in (Table 1).

2.2. Proteins

Various protein fractions are present in millets, such as albumins, globulins, cross-linked prolamins, and glutelins, among others. Millets are particularly rich in prolamin and glutelin fractions, surpassed by the combined albumin and globulin fractions. Pearl millet's prolamin content ranges between 22.8% to 31.7% of its total protein, while finger millet holds 24.6-36.2%, and foxtail boasts a significant 47.6-63.4%. When it comes to glutelin, finger millet leads with 12.4-28.2% of its total protein, compared to foxtail's 6.7%. The albumin plus globulin fraction varies between 11.6% to 29.6% across these millets.[2,3]

Pearl millet contains the highest average protein levels ranging from 6.9-12%. In contrast, fonio and finger millet have relatively lower protein values, registering 5.1-10.4% and 4.9-11.3%, respectively. Finger millet is notable for its lysine content at 5.5 g per 100 g of protein. Both Teff (2.0-4.0 g per 100g protein) and kodo millet (3.0-3.5 g per 100g protein) are also lysine-rich. On the other hand, Proso and Japanese millets are characterized by a less robust essential amino acid profile.[4]

Digestibility of millet proteins demonstrates a range, with the lowest seen in foxtail and barnyard millets (95%) and the highest in common millet (99.3%). Furthermore, the biological value and net protein utilization of pearl millet protein outpace that of minor millets. However, minor millets possess a superior digestible energy range (95.6-96.1) when juxtaposed with pearl millet's 85.3-89.9.[5,6]

2.3. Lipids

Millets exhibit a fat content that varies between 1% to 5%. Finger and kodo millet have the minimum fat content at 1%, while pearl, foxtail, and proso millets peak at 5%. This fat is evenly distributed throughout the bran and endosperm. Typically, the fat consists of an impressive 60% or more of unsaturated fatty acids, including linolenic acid. Common millet encompasses a lipid content between 1.8-3.9%. Notably, the embryo houses approximately 24% of the grain's overall fat. The fatty acid distribution reveals that saturated fatty acids are present in a range of 17.9-21.6%, whereas unsaturated fatty acids dominate at 78-82%.

In terms of seed dry weight, millets have an estimated lipid extraction of 7.2%. This fraction is categorized into neutral lipids (85%), phospholipids (12%), and glycolipids (3%). Out of the neutral lipids, a whopping 85% are triacylglycerols, while the remainder consists of minor quantities of mono- and diacylglycerols, free fatty acids, and sterols. Both campesterol and stigmasterol were detected in equal proportions in free and esterified forms. The primary phospholipid found in millet seeds was lysophosphatidylcholine at 42%. Other phospholipids present in minor amounts included lysophosphatidylethanolamine (21%), phosphatidylcholine (24%), and trace elements of other phosphatidyl compounds. Dominant glycolipids include sterol glycoside, esterified sterol glycoside, cerebrosides, monogalactosyldiacylglycerol, and digalactosyldiacylglycerol.[7]

2.4. Vitamins

Millets stand out as significant sources of Vitamin E and a spectrum of B-complex vitamins, with the exception of Vitamin B12. They contain a total niacin content of 10.88 mg, although only a fraction (13%) is extractable with cold water. Despite being nutrient-dense, mature millet grains exhibit low concentrations of Vitamin C. The tocopherol levels in millets are modest when compared to those in soybean and corn oil. Millet seeds predominantly feature the γ-isomer of tocopherols, while the α-tocopherol content remains minimal. It's worth noting that the vitamin activity of α-tocopherol substantially surpasses that of other tocopherols, with γ-tocopherol's Vitamin E activity being less than 10% of the α-tocopherol's activity. Fat extracted from the unrefined kernel of common millet showcases notable quantities of Vitamin A (ranging between 8.3-10.5 mg) and Vitamin E (between 87-96 mg) per 100 grams.[8]

Table 1: Nutrient composition ofMillets (Per 100 gm edible portion, Dry weight basis)

Source	Carbohydrates (g)	Crude Protein (g)	Fat (g)	Crude fiber (g)	Ash (g)	Energy (kcal)
Pearl Millet	60.0–76.0	12.0 –14.0	4.8 –5.7	2 –2.5	2.0–2.2	363–412
Finger Millet	60.0–80.0	7.0–10.0	1.3–1.8	3.6–4.2	2.6–3.0	328–336
Foxtail Millet	59.0–70.0	11.2–15.0	4.0–7.0	4.5–7.0	2.0–3.5	330–350
Kodo Millet	66.0–72.0	8.0–10.0	1.4–3.6	5.0–9.0	4.0–5.0	309–353
Little Millet	60.0–75.0	10.0–15.0	5.0–6.0	4.0–8.0	2.5–5.0	329–341
Barnyard Millet	55.0–65.0	6.0–13.0	2.0–4.0	9.5–14.0	4.0–4.5	300–310
Proso Millet	55.0–70.0	10.0–13.0	1–3.5	2.0–9.0	2.0–4.0	330–340
Teff	70.0–73.0	10.0–11.0	2.0–4.0	1.0–2.0	2.8–3.1	330–340
Fonio*	75.0–82.0	7.0–9.0	0.5–2.0	2.0–3.5	1.0–4.0	360–370

*Wet weight basis. Sources: McWatters et al. (2003), Gebremariam et al. (2014), Sadik et al. (2012), Gopalan et al. (1989), Saldivar, (2003), Ravindran (1991), Hulse et al. (1980), and National Research Council (US), Board on Science and Technology for International Development (Eds.) (1996)

However, the refining process considerably depletes the Vitamin A activity and induces significant losses in Vitamin E content. Among millets, little millet stands out with a niacin content that is comparatively higher than other cereals.

2.5. *Minerals*

The mineral composition of millets aligns closely with other cereals like sorghum. However, they notably excel in their calcium and manganese content [Refer to Table 2]. Research has indicated that certain high-yielding and high-protein varieties (8–12.1%) of finger millet possess calcium levels ranging from 294 to 390 mg/100 g.[9] A study by Joseph et al. in 1959, which explored the impact of substituting a rice-based diet with finger millet for 9–10-year-old girls, illustrated enhanced calcium retention and sustained positive nitrogen balance. Such findings suggest that finger millet can serve as an effective rice substitute to address calcium deficiencies.[10]

In terms of iron content, little millet and barnyard millet stand out with concentrations of 9–12%. On the other hand, kodo millet and common millet are especially abundant in copper. When it comes to overall mineral or ash content, common, little, foxtail, kodo, and barnyard millets surpass many popular cereals, including sorghum. It's worth noting that these millets typically have a fibrous hull, which is often removed before consumption. This dehulling process can significantly reduce the mineral content, with the extent of loss varying depending on the millet species."

3. Nutraceuticals Properties of Millets

The term "nutraceuticals," drawing a parallel to "pharmaceuticals," denotes bioactive compounds derived from food sources that, in their isolated form, offer protective benefits against degenerative diseases.

3.1. *Phenolic compounds*

Phenolic compounds are diverse, characterized by their aromatic rings that possess one or more hydroxyl groups and various substitutions. These compounds are generally grouped into phenolic acids, flavonoids, and lignans. They often exist as glycosides attached to sugar groups or complexed with organic acids, lipids, other carbohydrates, and additional phenols. Notably, Chethan and Malleshi (2007) highlighted significant differences in the polyphenol content across finger millet varieties, with brown types containing 1.2–2.3g% and white types having 0.3–0.5g%.[11] These compounds serve as crucial antioxidants, combating diseases related to oxidative stress, such as cancer and cardiovascular disease.

Research has indicated that kodo millet contains the highest quantity of bound polyphenols (extractable with 1% HCl), followed by foxtail, little millet, pearl millet, finger millet, and proso millet. Compared to rice, millets offer a richer source of these beneficial compounds.[12] Beyond their antioxidant properties, bound phenolic compounds also showcase antiobesity, antidiabetic, anticarcinogenic, antimicrobial, and antiviral benefits, including potential inhibitory effects on certain pathogens like HIV and the influenza virus. This emphasizes the importance of 1% acidic-methanol extracts from various millets as health-boosting polyphenol sources.

The antioxidant potential of phenolic compounds is attributed to their capacity to donate hydrogen atoms to free radicals lacking electrons, utilizing the hydroxyl groups on their benzene rings. This results in the creation of a stable and less reactive phenoxyl radical. Furthermore, polyphenols have been known to inhibit the actions of several digestive enzymes, such as amylase, glucosidase, pepsin, trypsin, and lipases.[13] As Pietta observed, polyphenolic substances like flavonoids, phenolic acids, and proanthocyanidins are significant due to their radical neutralizing activities and their potential role in preventing

Table 2: Mineral composition of millets (mg/100g)

Minerals	Pearl	Finger	Foxtail	Little	Proso	Kodo
K	440–442	408–570	250–400	129–370	250–320	144–170
Na	10.0–12.0	7.0–11.0	4.6–10	6–8.1	8.2–10	4.6–10
Mg	130–137	110–137	100&8209;130	120–133	117–153	130–166
Ca	10.0–46.0	240–410	10.0–30.0	12.0–30.0	20–23	10.0–31.0
P	350&8209;379	240–320	270–310	251–260	230–281	215–310
Mn	1.15–1.8	5–5.5	2.19–26	1.0–20.0	0.6–1.81	1.10–2.9
Zn	2.95–3.1	2–2.3	2.14–9	3.5–11	1.4–2.4	0.7–1.5
Cu	0.62–1.06	0.4–4	1–3.0	1.0–4.0	0.83–5.8	1.6–5.8
Fe	7.49–8.0	3.9–7.5	3.26–19	13–20	4.0–5.2	0.7–3.6

Sources: Varriano‑Marston and Hoseney, (1980), Serna‑Saldivar et al., (1991), Hulse et al., (1980), Serna‑Saldivar and Rooney, (1995), Pore, and Magar, (1979), Lorenz et al., (1976), Chung, (1991), Barbeau, and Hilu, (1993), Chavan, (1989), and Chavan, et al. (1989)

numerous ailments.[14] The inclusion of phenolic compounds in one's diet can potentially lower the risk of chronic diseases.[15] Additionally, the combined effects of various phenolics might influence amylase inhibition, making them potential aids in managing type 2 diabetes, which is characterized by elevated blood glucose levels.[16,17] As inhibitors of amylase and glucosidase (analogous to acarbose, miglitol, and voglibose), polyphenols can help reduce postprandial hyperglycemia.[18]

3.2. Phenolic acids

Phenolic acids are characterized by a benzene ring coupled with a carboxylic acid group. These acids mainly stem from benzoic acid derivatives (with a C6-C1 structure) and are primarily divided into hydroxybenzoic and hydroxycinnamic acid derivatives. The hydroxybenzoic category encompasses acids like protocatechuic, vanillic, syringic, gallic, and hydroxybenzoic. They predominantly exist in bound forms, often as components of intricate structures like lignins and hydrolyzable tannins.

On the other hand, the hydroxycinnamic group consists of acids like p-coumaric, caffeic, ferulic, and sinapic. These acids are typically found in a bound state, attached to cellular structures such as cellulose, lignin, and proteins through ester linkages. Notably, finger millet grains contain a variety of phenolic acids, including the likes of ferulic, vanillic, caffeic, syringic, and p-coumaric acids.[19]

Ferulic acid, known scientifically as trans-4-hydroxy-3-methoxycinnamic acid, stands out as a prevalent phenolic acid in finger millet grains.[20,21] This acid is predominantly located in the aleurone, pericarp, and embryo cell walls of various grains. However, its presence in the starchy endosperm is relatively minimal.[22,23]

3.3. Flavonoids

Flavonoids are a diverse group of plant-based compounds with a fundamental 15-carbon skeleton, comprising two phenyl rings and a heterocyclic ring. Originating from phenylalanine[24] flavonoids possess a primary C6-C3-C6 configuration. This extensive family of polyphenolic compounds, ubiquitous in fruits and vegetables, features structures like anthocyanin pigments, flavonols, flavanols, and isoflavones. While most exist as glycosides, flavanols often polymerize into condensed tannins. Tannins can be broadly categorized as condensed or hydrolyzable. The former usually are polymers of flavan-3-ols or flavan 3, 4 diols, whereas the latter are generally esters of glucose with either gallic acid or hexahydrodiphenic acid.

Health-promoting flavonoids such as catechin, quercetin, anthocyanin, and tannin are known for their antioxidant attributes. Their ability to neutralize radicals[25] stems from the specific arrangement of hydroxyl groups in their structure and the inclusion of certain electron-donating and withdrawing groups. Miller et al. in 2000 highlighted that, on a per-serving basis, whole grains exhibit antioxidant capabilities comparable to those of fruits and vegetables.[26] Among flavonoids, only flavones have been reported in millets. For instance, finger millet leaves house eight distinct flavones, including vitexin and isovitexin.[27] Pearl millet contains flavones that contribute to a yellow-green hue at basic pH.[28] Japanese barnyard millet boasts compounds like luteolin and tricin,[29] while fonio has concentrations of apigenin and luteolin,[30] with a significant portion in free form. Notably, only finger millet has been documented to contain condensed tannins, with brown varieties showing higher amounts than white ones.[31] However, comprehensive studies detailing the structural nuances of millet proanthocyanidins are scant.

3.4. Phytic acid

Phytic acid, also recognized as myoinositol 1,2,3,4,5,6 hexakis-dihydrogen phosphate, is found in varying concentrations in foods, typically between 0.1 to 6.0%.[32,33] Reddy et al. in 1982 pinpointed its location mainly in the bran region of cereal grains and within the protein bodies of the cotyledons in oilseeds or legumes.[34] Lorenz highlighted that the phytate content in standard millet varieties fluctuates between 170 and 470 mg per 100g of whole grain. It was also observed that dehulling led to a substantial reduction in phytate content, with a drop of 27–53%. Specifically, dehulling resulted in reductions of 12% in common millet, 39% in little millet, 25% in kodo millet, and 23% in barnyard millet.

4. Carotenoid and Tocopherols

Food sources offer a rich variety of pigments, with carotenoids being prominent among them. Over 600 distinct carotenoids have been discovered to date. Besides their well-recognized role as provitamin-A agents, carotenoids play a vital role in shielding against multiple diseases, thanks to their antioxidant properties. Structurally, they are made up of isoprenoid units linked in a lengthy polyene chain that features between 3 to 15 conjugated double bonds. The location of these double bonds influences their absorption spectra. Carotene undergoes a cyclization process at either one or both ends, whereas xanthophylls emerge with the introduction of oxygen. Additionally, they can undergo various structural alterations, including isomerization, chain extension, or even degradation.

A recent study by Asharani and colleagues revealed variations in the total carotenoid content in different millet flours. Specifically, the average values were 199 μg/100 g for finger millet, 78 μg/100 g for little millet, 173 μg/100 g for foxtail millet, and 366 μg/100 g for proso millet.[35] When compared to other grains, the carotenoid levels in millets were in line with those of wheat (ranging between 150-200 μg/100 g) and sorghum (180-230 μg/100 g). However, they were markedly lower than the levels found in maize, which ranges from 1800-5500 μg/100 g, and its specific varieties, which have content between 2400-3200 μg/100g.[36]

Vitamin E, a fat-soluble element, is abundantly present in nature and belongs to a diverse family of eight molecules. Although each molecule has distinct structural differences, they all share a chromanol ring and a 12-carbon aliphatic side chain. This chain features two methyl groups, positioned both centrally and terminally. The Vitamin E family encompasses 4 tocopherols and 4 tocotrienols, each having three double bonds. These groups further branch into four variants: alpha, beta, gamma, and delta, differentiated by the number of methyl groups in their chains. When analyzed using HPLC, millets predominantly contain higher amounts of γ- and α-tocopherols, with reduced tocotrienol levels. Notably, finger and proso millet varieties have a total tocopherol content between 3.6–4.0 mg/100 g, which is more significant than what's found in foxtail and little millet varieties, approximately 1.3 mg/100 g. Beyond its nutritional value, Vitamin E serves as an antioxidant, plays roles in anti-inflammatory responses, reduces superoxide generation in mitochondria, and acts as an anti-atherosclerotic agent.

4.1. *Phytosterols*

Phytosterols, also known as desmethyl sterols, possess a ring structure that closely resembles cholesterol. They play a vital role in the structure and function of plant cells. Due to their structural similarity to cholesterol, they effectively reduce serum cholesterol by modifying the absorption rate of both ingested and internally produced cholesterol. Notably, phytosterol esters can decrease LDL cholesterol in the blood by as much as 14%, while having no impact on HDL levels.[37]

Consuming phytosterols daily can decrease heart disease risk by up to 40%, though this effect varies based on age and other factors. However, the intake of sterols can hinder the absorption of nutrients like alpha and beta-carotene, as well as Vitamin E. Certain processes, such as etherification, emulsification, and solubilization, can negatively impact the bioavailability of these sterols. Studies indicate that finger millet has a sterol content of 0.149% based on seed weight, while other millets have only negligible amounts. In comparison, sorghum and corn have a reported phytosterol content of 0.5 mg/g and 0.9 mg/g, respectively.

4.2. *Arabinoxylans*

Arabinoxylans belong to the hemicellulose family and are key components of both primary and secondary plant cell walls. Comprised of 1,4-linked xylose chains interspersed with 2,3-linked arabinose residues,[38] these components are considered dietary fibers due to their non-digestible nature. Dietary fibers not only add bulk to our diet but also play a pivotal role in cholesterol management. For instance, finger millet bran has a xylooligosaccharide content of 15.60%, compared to 40% in wheat bran and 9.33% in corn bran.[39]

During the processing of cereals, baking of bread, brewing of beer, and fermentation in the colon by bacteria, arabinoxylans undergo enzymatic breakdown to produce arabinoxylan-oligosaccharides (AXOS). This category includes both arabinoxylooligosaccharides and xylooligosaccharides (XOS). Both AXOS and XOS have demonstrated prebiotic properties by favorably influencing gut microbiota in humans and animals.[40] Large-scale studies have further emphasized the beneficial impacts of dietary fibers, linking them to reduced risks of ailments such as type II diabetes,[41,42] cardiovascular diseases,[43,44] and gastrointestinal cancers.[45,46]

5. Conclusion

Millets, primarily grown in tropical and semiarid regions, stand out for their adaptability to harsh conditions like drought, heat, and pest infestations, making them particularly resilient when traditional cereals might not yield sustainably. Notably, about 90% of global millet production is used in developing nations, with two-thirds serving as a dietary staple. Often labeled as sustenance for the economically disadvantaged, millets offer nutritional value on par with widely-consumed cereals like rice, wheat, and barley.

The health advantages linked with millets predominantly arise from their rich phytochemical content, including polyphenols, tocopherols, phytosterols, and dietary fiber. Additionally, millets are a good source of essential vitamins, minerals, and trace elements. While animal studies have robustly demonstrated the health benefits of millets, human research, including both epidemiological and experimental studies, is still in its infancy. However, some existing studies suggest that regular millet consumption can potentially reduce the risk of chronic diseases such as diabetes, cardiovascular disorders, and certain cancers. Consequently, integrating a diverse range of fruits, vegetables, and millets into daily diets can be a proactive step towards better health and warding off chronic illnesses.

Despite their health benefits, millets have yet to gain significant traction in developed countries, where diet-induced chronic ailments are on the rise. Misconceptions about millets being a "poor man's food" persist, and there's a clear need for more advanced processing techniques, machinery, and standardized products in the millet industry. For millets to rival the popularity of mainstream cereals, efforts should be channeled towards production innovation, cost-reduction, and creating a wide range of processed products that are both beneficial and appealing to consumers. Given their proven health advantages, it's high time for millets to be promoted and celebrated as a premier dietary choice.

6. Source of Funding

None.

7. Conflict of Interest

None.

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Author biography

Narendra Kumar Ahirwar, Senior Researcher

Ravindra Singh , Professor

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