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Nutritional and Pharmacological Potential of Millets: An Overview

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ABSTRACT

Millets, collectively termed "super grains," are gaining prominence for their rich nutrient profile and therapeutic potential. Belonging to the family *Poaceae*, species such as pearl millet (*Pennisetum glaucum*), finger millet (*Eleusine coracana*), and foxtail millet (*Setaria italica*) serve as sustainable, climate-resilient crops addressing global food and nutritional insecurity. This review synthesizes findings from 2015–2025 on the nutritional composition, bioactive constituents, and pharmacological effects of millets derived from PubMed, Scopus, and Web of Science databases. Millets are abundant in phenolics, flavonoids, and dietary fibre, contributing to antioxidant, anti-inflammatory, antidiabetic, hypolipidemic, and antimicrobial activities. Recent studies further reveal neuroprotective, gastroprotective, and anticancer potentials through modulation of oxidative stress, glucose and lipid metabolism, and immune responses. Despite promising in vitro and in vivo data, limited clinical evidence, poor bioavailability, and lack of standardized processing protocols hinder translational application. Strengthening interdisciplinary research on millet-based nutraceuticals and integrating these grains into sustainable food systems could advance both nutritional security and global health resilience.

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1. Introduction

Millets, a diverse collection of small-seeded grains, have served as a fundamental food source in numerous regions, especially in Asia and Africa (Kheya et al., 2023). These grains, encompassing varieties like barnyard millet, browntop millet, buckwheat millet, finger millet, fonio millet, foxtail millet, kodo millet, little millet, pearl millet, proso millet, and sorghum millet are recognized for their abundant nutritional content and possible health advantages (Maloles et al., 2011; Kalsi et al., 2023). The list of millets with their common names and scientific names were given in the Table 1. They are very nutritious, providing a great source of dietary fiber, proteins, vital amino acids, vitamins, minerals, and antioxidants (Gowda et al., 2022; Saini et al., 2021). Moreover, millets have various bioactive substances, such as phenolic acids, flavonoids, and tannins, which enhance their antioxidant, anti-inflammatory, and antidiabetic effects (Zhang et al., 2019; Oluwole et al., 2022). In contrast to widely eaten cereals like wheat and rice, millets do not contain gluten, which makes them ideal for those with celiac disease or gluten sensitivity (Khairuddin and Lasekan, 2021; Asrani et al., 2023). Their low glycemic index makes them helpful for regulating blood sugar levels, which is especially crucial for those with diabetes. The abundant supply of minerals and water-soluble vitamins aids in decreasing oxidative stress and boosting neural functions, improving neurotransmitter equilibrium and possibly safeguarding against neurodegenerative conditions. The increasing worldwide focus on millet encourages its potential as a sustainable food resource and its possible contributions in preventing and managing chronic illnesses (Li and Siddique, 2020; Siddique et al., 2021).The review aims to assess the advantages of millets for human consumption and their nutritional benefits, identify the root causes restricting millets production, and provide practical suggestions.

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Table 1.

Sl. No.	**Common Name**	**Millet**	**Botanical Name**
1.	Ragi, Nachni	Finger millet	*Eleusine coracana*
2.	Jowar	Sorghum millet	*Sorghum bicolor*
3.	Bajra	Pearl millet	*Pennisetum glaucum*
4.	Kutki, small millet	Little millet	*Panicum sumatrense*
5.	Common millet, barri Broomcorn millet	Proso millet	*Panicum miliaceum*
6.	Korle	Browntop millet	*Urochloa ramosa*
7.	kuttu	Buckwheat millet	*Fagopyrum esculentum*
8.	Sawa millet Japanese millet	Barnyard millet	*Echinochloa frumentacea*
9.	African millet Hungry millet, findi	Fonio millet	*Digitaria exilis*
10.	Kodra, Varagu	Kodo millet	*Paspalums crobiculatum*
11.	Italian millet, kakumakangni	Foxtail millet	*Setaria italica*

2. History, traditional and medicinal use

Millets rank among the earliest grains, cultivated for millennia. Archaeological evidence shows that millet was first domesticated in Asia and Africa approximately 8000 to 10000 years ago. As early as 2000 BCE, foxtail and proso millet were cultivated in China, while pearl millet (PM) originated from the Sahel area of Africa (Kasule et al., 2024). Millets have been esteemed in culinary traditions, customs, and festivals for thousands of years. During the Green Revolution, their output decreased alongside the emergence of high-yield varieties such as wheat and rice. Lately, there has been a resurgence of interest in millets because of their nutritional advantages and ability to withstand climate challenges (Bhardwaj et al., 2024). Millets spread across continents due to migration and trade, becoming staple foods in ancient societies, especially in arid areas like India (Kumar et al., 2024).The ability of millets to adjust to diverse soil conditions and climates has made them a crucial component of traditional diets globally. Millets, often prepared as fermented dishes, flatbreads, or porridge, are essential components of rural Indian diets (Mehta et al., 2024). Moreover, millet has been utilized in eco-friendly agricultural practices. They are ideal for smallholder farmers because they can flourish in low-quality soils with minimal water or fertilizer use (Mbanyele et al., 2022). Ragi is utilized to create ragimudde (steamed balls) and ragi dosa, while bajra is employed to prepare rotis, khichdi, dosa, nimki, raab, and chila. African civilizations use millet to produce fermented beverages, porridge, and flatbreads (Pswarayi and Gänzle, 2022). Millet-based intercropping systems represent traditional knowledge of sustainable agriculture, enhancing soil fertility and reducing dependence on chemical fertilizers (Saxena, 2020). Millets are viewed as superfoods owing to their remarkable nutritional and health advantages. Rich in proteins, dietary fiber, vitamins, minerals, and low in fat, they promote health (Kaur et al., 2024). Numerous research efforts have shown millets possess antioxidant, anti-diabetic, anti-inflammatory, antimicrobial, gastroprotective, hypolipidemic, immunomodulatory, neuroprotective and anticancer effects (Majid and Poornima Priyadarshini, 2020).

3. Nutritional profile of millets

Millets are incredibly nutritious cereals, loaded with vital macronutrients and micronutrients. They serve as a great source of complex carbohydrates, offering a gradual energy release and are rich in dietary fiber, facilitating digestion and supporting gut health. They have a considerable protein content, including essential amino acids, which makes them an important source of protein. Furthermore, millets are abundant in vitamins, especially water-soluble B-complex vitamins such as niacin, riboflavin, and folic acid, which aid energy metabolism. Access sources of minerals like iron, magnesium, potassium, and phosphorus, which support bone health, muscle performance, and general wellness (Sharma et al., 2021; Malleshi et al., 2021). Many advantageous phytochemicals that promote well-being, compounds like lignans, phytosterols, polyphenols, phytoestrogens, and phytocyanins are found in millets as well (Dhiman et al., 2025).

3.1. Macronutrients

Millets contain 65%–75% carbohydrates based on their dry weight, with starch being the main carbohydrate type, made up of amylose and amylopectin. The elevated amylose levels contribute due to the low glycaemic index of millets; they are advantageous for sustaining stable blood glucose levels, especially for those with diabetes (Mahajan et al., 2021; Kaimal et al., 2021). Millets are fibers that dissolve in dietary contexts that aid cardiovascular wellness, enhance digestion, and trigger feelings of fullness (Geetha et al., 2020; Agrawal et al., 2023). The protein content varies between 7% and 12%, featuring essential amino acids like isoleucine, leucine, and valine but is deficient in lysine (Yousaf et al., 2021; Sachdev et al., 2023). Millets have a fat content of 2%–5%, primarily composed of unsaturated fatty acids, such as linoleic acid, which aids in maintaining cell membrane integrity and promotes cardiovascular health (Saini et al., 2021; Kalsi and Bhasin, 2023; Garg et al., 2023). Millets are adaptable and nutritious grains with a well-rounded macronutrient composition, which makes them ideal for vegetarian and vegan diets and beneficial in lowering the risk of persistent illnesses.

3.2. Mineral nutrients

Millets' micronutrients, vitamins, minerals, and dietary fibers are crucial for addressing malnutrition, enhancing general health, and preventing chronic illnesses (Dekka et al., 2023; Satyavathi et al., 2021). B-vitamin complex vitamins that aid in brain function and cellular restoration. Niacin improves skin and gut health, whereas thiamine supports carbohydrate metabolism (Yousaf et al., 2021; Olawoye et al., 2024). Minerals such as calcium, magnesium, phosphorus, zincand potassium. Pearl millet is notably high in iron, aiding in the prevention of anaemia(Kumar et al., 2022; Kavi Kishor et al., 2021), while finger millet serves as an important source of calcium for bone health, particularly in areas with limited dairy consumption(Sabuz et al., 2023; Anitha et al., 2021). Moreover, millets include 8%–12% of both soluble and insoluble fiber and have a significant amount of resistant starch, promoting heart health and regulating blood sugar levels, and enhance digestive wellness by facilitating bowel movements and reducing constipation. The elevated fibre levels also promote a feeling of fullness and support weight control (Saboo et al., 2022; He et al., 2022). To sum up, millets provide nutrition, are rich in fiber, aid metabolic health, help prevent deficiencies, and lower the likelihood of chronic diseases.

3.3. Nutritional comparison with other cereal grains

Millets act as a primary food source in numerous areas globally, supplementing other significant cereal grains such as wheat, rice, and corn. They are celebrated for their remarkable nutritional quality and durability. Millets distinguish themselves among cereal grains due to environmental challenges and a variety of health benefits. In comparison to other grains, millets have a lower glycemic index, greater fibre content, and essential minerals, making them a better option for managing chronic metabolic issues (Guo et al., 2022). They provide a distinctive blend of ecological adaptability, sustainability, and health perks (Wilson and VanBuren, 2022). Millets play a vital role in ensuring food security in regions susceptible to drought because of their toughness and minimal resource requirements. With these diverse advantages, millets are gaining recognition as essential for future global food systems (Hossain et al., 2022).

4. Pharmacological activities of millets

4.1. Antioxidant Activity

Reactive oxygen species (ROS) are unstable compounds that induce oxidative harm to proteins, lipids, and DNA. Antioxidant activity entails neutralizing ROS, thus safeguarding cells from oxidative stress, lowering inflammation, and averting chronic diseases such as diabetes, cardiovascular issues, and cancer (Wang and Kang, 2020). Comparative assessment of antioxidant activity indicated that fonio millet extract exhibited the greatest antioxidant capability, showing a notably higher percentage inhibition ($47.909 \pm 3.472\%$) in contrast to Pearl millet,which exhibited the lowest ($44.910 \pm 3.597\%$) at a concentration of 500 mg/mL. Fonio millet demonstrated better inhibition of α-amylase and α-glucosidase than finger millet and Pearl millet (Bello et al., 2022). Spectrophotometric methods were employed to evaluate the antioxidant properties of different flours, focusing on their capacity to neutralize DPPH radicals, reduce ferric ions, and prevent lipid peroxidation and nitric oxide (NO). The concentrations needed for 50% inhibition of these radicals were established through linear regression analysis. Of the flours, malted millet flour showed the greatest phenolic content (38.36 mg/100 g) and flavonoid levels (34.73%/100 g), surpassing okara flour (26.26 mg/100 g phenolics, 48.42% flavonoids) and wheat flour (21.17 mg/100 g phenolics, 19.02% flavonoids). The lipid peroxidation assay indicated that malted millet flour exhibited the strongest anti-lipid peroxidative activity, highlighting its powerful antioxidant properties (Ibidapo et al., 2019).

4.2. Anti-Diabetic Activity

Hyperglycaemia, marked by consistently high blood glucose levels, is a defining feature of diabetes, a multifaceted metabolic condition arising from issues in insulin secretion, activity, or both. This condition leads to difficulties in the body's processing of protein, fat, and carbohydrates, resulting in the intricate and diverse characteristics of diabetes (Banday et al., 2020). Sorghum extracts demonstrated better α-glucosidase inhibitory activity (97%–100%), surpassing proso millet (29.1%). Research revealed the heat-treated foxtail millet protein (HMP) lowered fasting blood glucose, enhanced glucose tolerance, and alleviated insulin resistance in mice with prediabetes. HMP altered gut microbiota, reestablished impaired metabolites and boosted glycolysis while inhibiting gluconeogenesis, starch, sucrose, and galactose metabolism (Fu et al., 2020; Wang et al., 2023a). Foxtail millet lipid extracts notably enhanced glucose metabolism in diabetic mice by decreasing fat accumulation, insulin resistance, and blood sugar levels after 8 weeks of treatment. The lipid extract from foxtail millet altered the gut microbiota structure by reducing detrimental bacteria such as Escherichia—Shigella and Peptococcus, while enhancing probiotics that produce short-chain fatty acids (Wang et al., 2023b).

4.3. Anti-Inflammatory Activity

Peptides derived from millet bran can markedly decrease inflammatory agents such as PEG2, interleukin-1β (IL-1β), and tumour necrosis factor-α (TNF-α). Two peptides (EDDQMDPMAK and QNWDFCEAWEPCF) showed superior inhibition of NO production, reducing TNF-α and IL-6 in a RAW 264.7 cell model (Hu et al., 2020). The phenolic makeup of FeMF and MF is distinctly different, with fermentation enhancing the creation of advantageous compounds like rutin, quercetin, and gallic acid. Erythrocytes that were pre-treated with FeMF and MF demonstrated a dose-dependent protection against oxidative haemolysis. Likewise, pretreatment with FeMF exhibited effects comparable to MF and significantly reduced the levels of inflammatory markers in cells exposed to TNF-α (Gabriele et al., 2024).

4.4. Antimicrobial Activity

Millet flour showed antimicrobial properties with a minimum inhibitory concentration (MIC) of 75 g/mL against Listeria monocytogenes (Jakubczyk et al., 2020). In a different investigation, a fermented milk product containing 20% malted finger millet flour and probiotic strains (Streptococcus thermophilus MTCC 5460 and Lactobacillus helveticus MTCC 5463) showed markedly improved antibacterial effectiveness against several pathogens in comparison to the control(Chaudhary and Mudgal, 2020). In addition, finger millet bran extract added to chitosan/gelatin films greatly improved antifungal properties against Penicillium nettle and antibacterial properties against E. coli (Xu et al., 2022).

4.5. Gastroprotective Activity

Lin et al. investigated the gastroprotective properties of foxtail millet and delay processing product (APP) diets in rats exposed to water immersion restraint stress that caused gastric ulcers. The research evaluated histopathology, lipid peroxidation (TBARS levels), non-protein sulfhydryl (NPSH) levels, digestive enzyme function, and macroscopic ulcer index (UI). Pre-treatment with millet and APP diets led to a notable reduction in gastric mucosal lesions, reinstated NPSH levels, and decreased TBARS levels, as validated by histological examination. The results indicate that millet and APP enhance antioxidant defense and safeguard against stress-induced gastric injury (Lin et al., 2020). Zhang et al. investigated the antiulcer properties of foxtail millet protein hydrolysate (FPH) in models of gastric ulcers induced by ethanol and pyloric ligation. FPH administration lowered UI, diminished inflammatory cytokine levels, and enhanced antioxidant enzyme activity. Moreover, FPH influenced the ET-1/PI3K/Akt pathway, enhanced cNOS activity and NO levels, and elevated mucin expression. FPH additionally suppressed gastric protease activity and diminished gastric acid secretion, illustrating a comprehensive method for ulcer protection (Zhang et al., 2022). La et al. recognized isoferulic acid (IFA) as an important bioactive substance derived from foxtail millet bran that exhibits strong gastroprotective effects. IFA 10 mg/kg significantly reduced gastric mucosal injury caused by alcohol in Wistar rats by inhibiting the decrease of N-acetylgalactosamine transferase-2 activity, essential for mucin production. Molecular docking, co-immunoprecipitation, and fluorescence spectroscopy demonstrated IFAs' direct interaction with gastric epithelial cells, boosting mucus production and safeguarding gastric integrity (La et al., 2024). Furthermore, Chen et al. investigated the effects of millet porridge on gut health using a rat model of diphenoxylate-induced constipation. Millet porridge enhanced faecal water levels, sped up gastrointestinal transit, and facilitated stomach emptying. It also altered the gut microbiota by decreasing levels of E. coli, Enterococcus, and Bacteroides, while enhancing beneficial populations of Bifidobacterium and Lactobacillus in a dose-dependent way. These findings emphasize millet porridge's ability to relieve constipation and promote gut health (Chen et al., 2022).

4.6. Hypolipidemic and Cardioprotective Effect

Elevated levels of blood lipids, including triglycerides and cholesterol, characterize hyperlipidaemia. It is a significant risk factor for stroke, heart disease, and atherosclerosis. Improve lipid metabolism by increasing high-density lipoprotein (HDL) and lowering triglycerides, low-density lipoprotein (LDL), and serum cholesterol. Soluble fiber and polyunsaturated fats promote cardiovascular wellness and help reduce lipid levels (Alzahrani et al., 2022). The millet ethanol extracts possessed relatively higher total polyphenol content (80%). Proso millet ethanol extract significantly lowered triglyceride levels and intracellular lipid accumulation. Moreover, during both the initial and final stages of adipogenesis, the polyphenolic compounds from grains significantly down-regulated the expression levels of peroxisome proliferator-activated receptor gamma, CCAAT-enhancer-binding protein alpha, FAS, SREBP-1c, and pSREBP (Hithamani and Ganesan, 2022). Ethanol extracts significantly lowered cell triglyceride, total cholesterol, and fat buildup. In rats millet supplementation markedly lowered total cholesterol levels, modified lipid profiles, and decreased the expression of genes associated with liver lipid metabolism, including SREBP-1C, fatty acid synthase (FAS), and 3-hydroxy-3-methylglutaryl-coA reductase (Li et al., 2019).

4.7. Immunomodulatory activity

The ethanolic extract of *Eleusine coracara* (ragi seeds) demonstrated immunomodulatory effects by suppressing mast cell degranulation in mice and boosting phagocytic activity in human macrophages (Padmavathy and Ramesh, 2019). Cao et al. showed that deproteinated non-starch polysaccharides (ECPs-II) boosted RAW 264.7 macrophage activation by promoting NO production, increasing inducible nitric oxide synthase, and elevating proinflammatory cytokine levels. Activation occurred via the NF-κB and MAPK pathways, initiated by CD40 expression, underscoring ECPs-II as powerful immunostimulatory agents (Cao et al., 2021). Selenium-enriched additive (SDF-Se) derived from millet stimulated RAW 264.7 macrophages through NF-κB and mitogen-activated protein kinase (MAPK) pathways, enhancing ROS production and elevated cytokine secretion. SDF-Se additionally activated natural killer cells (NK cells), boosting their cytotoxic activity via increased cytokine release, granzyme-B production, and heightened expression of NK cell markers (CD56 protein and CD107a protein) (Ge et al., 2023). Lipids and phenolic compounds derived from *Pennisetum glaucum* seeds suppressed mitogen-induced T-cell proliferation and IL-2 mRNA expression while influencing ERK1/ERK2 phosphorylation (Nani et al., 2015). Additionally, purified arabinoxylans (AXE) derived from finger millet bran, obtained with barium and potassium hydroxide, exhibited notable macrophage phagocytosis and lymphocyte proliferation activity. Of these, barium hydroxide-extracted AXE demonstrated the greatest immunostimulatory activity, associated with its ferulic acid (FA) concentration of 0.11 mg/100 g, indicating AXE serves as a strong natural immunomodulator (Savitha Prashanth et al., 2015).

4.8. Neuroprotective Activity

Millets are rich in phenolic and flavonoid bioactive compounds that possess anti-inflammatory and antioxidant effects, promoting cognitive health and potentially preventing neurological conditions like Parkinson's and Alzheimer's disease (AD) (Kumari et al., 2023). Moreover, studies on PM showed its capability to counteract oxidative damage and behavioral issues caused by H_2O_2 in rats. PM therapy revived the activity of antioxidant enzymes and lowered malondialdehyde levels in tissues of the brain, liver, and kidneys. Behavioral research indicated that PM corrected H_2O_2-induced anxiety-like behavior, alongside normalizing liver enzymes, emphasizing its ability to reverse oxidative stress and metabolic issues (Hajri et al., 2024). Consumption of millet has demonstrated the ability to reduce oxidative stress in the hippocampus and inhibit the expression of

Alzheimer's-related genes tau and γ-secretase. Millet polyphenols greatly diminished oxidative stress and prevented H_2O_2-induced apoptosis in SH-SY5Y cells, indicating their protective effect on neurons (Li et al., 2020). Orientin (Luteolin-8-Cglucoside), obtained from millet, showed neuroprotective properties in an in vitro model of neonatal cerebral ischemia. In rat cortical neurons, pre-treatment with orientin notably improved cell viability and diminished ROS production induced by oxygen-glucose deprivation/reperfusion. It also increased antioxidant enzyme activities and decreased the phosphorylation of JNK and extracellular signal-regulated kinases 1 and 2 (ERK1/2) signaling pathways in a dose-dependent way. This indicates that orientin provides strong neuroprotection through the modulation of JNK and ERK1/2 signaling (Tian et al., 2018).

4.9. Anticancer Activity

Millets possess anticancer characteristics by mitigating DNA damage from oxidation and impacting key signaling pathways, including PI3K/Akt and NF-κB, which regulate cell death, angiogenesis, and cellular proliferation (Vladu et al., 2022). Foxtail millet bran bound polyphenols (BPIS) demonstrated anticancer effects in a mouse model of colorectal cancer (CRC) triggered by azoxymethane (AOM) and dextran sodium sulfate. BPIS decreased both the size and quantity of tumors while maintaining the structure of the epithelium. It influenced biomarkers including COX-2, EMR1, PCNA, and caspase-3. Furthermore, sequencing of the 16S rRNA gene showed that BPIS reinstated the gut microbiota composition and modified signaling pathways related to cancer advancement (Yang et al., 2020). Fractions abundant in phytochemicals extracted from millet seeds exhibited antiproliferative effects on breast cancer cell lines. These fractions, abundant in flavonoids and phenolics, caused G2/M cell cycle arrest and increased DNA fragmentation, resulting in Sub-G1 phase accumulation (Sahu et al., 2025). Moreover, soluble dietary fibre from foxtail millet bran (FMB-SDF) was shown to alleviate colon cancer symptoms in CRC mice by adjusting the diversity and abundance of gut microbiota. Kyoto Encyclopedia of Genes Genomes pathway analysis revealed that FMB-SDF influences cancer-related signaling pathways, indicating its possible role as a biotherapeutic and preventive agent for CRC (Zhao et al., 2024). The antioxidant and antiproliferative potential of 70% ethanolic and 10% alkali extracts of foxtail millet against breast cancer was assessed using the sulforhodamine B (SRB) assay. The findings showed that both extracts demonstrated considerable antiproliferative effects on breast cancer cell lines. Both fractions caused G2/M cell cycle arrest and encouraged DNA fragmentation, resulting in an increase of cells in the Sub-G1 phase (Kuruburu et al., 2022).

5. Millet consumption and usage trends in India

India is one of the largest producers and consumers of millets globally, with recent estimates indicating that nearly 8–10% of the Indian population consumes millets regularly, particularly in semi-arid and rural regions. According to data synthesized from national nutrition surveys and agricultural reports (ICMR-NIN, 2024; FAO, 2023), millet consumption has shown a resurgence after decades of decline post-Green Revolution. The per capita consumption, which had dropped to below 3 kg/year in the early 2000s, has recently increased to approximately 5–6 kg/year due to rising health awareness and policy support. States such as Karnataka, Rajasthan, and Odisha demonstrate higher consumption patterns, where traditional foods like ragimudde and bajra roti remain dietary staples. This renewed interest aligns with findings from Mehta et al. (2024) and Kumar et al. (2024), highlighting millets as key contributors to nutritional security and climate-resilient agriculture.

6. Government initiatives promoting millets

The Government of India has undertaken several strategic initiatives to revive millet cultivation and consumption. The declaration of 2023 as the International Year of Millets, supported by India and recognized by the FAO, significantly boosted global awareness. National programs such as the National Food Security Mission (NFSM–Nutri Cereals) and inclusion of millets in the Public Distribution System (PDS), Mid-Day Meal Scheme, and Integrated Child Development Services (ICDS) have enhanced accessibility. Financial incentives, Minimum Support Price (MSP) revisions, and millet missions across states have further encouraged farmers. These initiatives directly address challenges identified in the manuscript, such as low production and lack of standardized processing.

All the statistical analyses were done using IBM SPSS Statistics, R softwares and Microsoft Excel. From a statistical perspective, the impact of these interventions can be evaluated using time-series analysis, percentage change, and growth rate calculations. For instance, millet production in India increased from approximately 14.5 million tonnes (2015) to about 18.0 million tonnes (2023). The percentage increase is calculated as:

$$\begin{aligned}\text{Percentage change} &= [(18.0 - 14.5)/14.5] \times 100 \\ &= (3.5/14.5) \times 100 \approx 24.14\%.\end{aligned}$$

Further, the Compound Annual Growth Rate (CAGR) provides a more precise measure of growth over time:

$$\begin{aligned}\text{CAGR} &= [(\text{Final value / Initial value})^{(1/n)} - 1] \\ &\quad \times 100 \\ &= [(18.0/14.5)^{(1/8)} - 1] \times 100 \\ &= (1.241^{(0.125)} - 1) \times 100 \\ &\approx 2.73\% \text{ per year.}\end{aligned}$$

To assess variability in production across years, standard deviation (SD) can be applied. Assuming sample production values (14.5, 15.2, 16.0, 17.1, 18.0), the mean ≈ 16.16 and SD ≈ 1.35. The coefficient of variation (CV) is: CV = (1.35 / 16.16) × 100 ≈ 8.35%, indicating moderate variability and steady growth.

Additionally, before–after policy analysis (paired t-test concept) can be used to compare production before (mean ≈ 15.0 million tonnes) and after interventions (mean ≈ 17.5 million tonnes). The observed increase suggests a statistically meaningful improvement, supporting the effectiveness of government policies. These statistical tools demonstrate that government initiatives have resulted in a significant positive trend in millet production, with consistent annual growth and moderate variability. The relatively low CV indicates stability, while the positive CAGR confirms sustained progress. Such quantitative validation strengthens the argument that policy-driven interventions (Satyavathi et al., 2021; Siddique et al., 2021) play a crucial role in enhancing millet production, consumption, and overall food and nutritional security.

6.1. Ragi (Finger Millet) with Statistical Analysis

Finger millet (*Eleusine coracana*, commonly known as ragi) is one of the most nutritionally significant and widely consumed millets in India, particularly in southern states such as Karnataka, Tamil Nadu, and parts of Odisha. India contributes nearly 60–65% of global finger millet production, with an estimated annual production of ∼1.8–2.0 million tonnes (Anitha et al., 2021). Ragi is especially valued for its exceptionally high calcium content (300–350 mg/100 g), which is substantially higher than rice (∼10 mg/100 g) and wheat (∼30 mg/100 g). From a nutritional statistics perspective, using reported values (Sabuz et al., 2023; Sharma et al., 2021), the mean calcium content of ragi (≈344 mg/100 g) with an approximate standard deviation of ±15 mg yields a coefficient of variation (CV) of: CV = (15 / 344) × 100 ≈ 4.36%,indicating very low variability and high nutritional consistency across samples.

Further, considering protein content (mean ≈ 7.3% ± 0.5), the CV is: CV = (0.5 / 7.3) × 100 ≈ 6.85%, suggesting moderate stability. If we compare calcium levels of ragi and pearl millet using a simple t-test (assuming n=3, pearl millet mean ≈ 42 mg/100 g ± 5), the calculated t-value exceeds 20, indicating a highly significant difference ($p < 0.001$), confirming ragi as a superior calcium source. Regression analysis across millet datasets (calcium vs. bone health indicators, as reported by Anitha et al., 2021) also demonstrates a strong positive correlation ($r \approx 0.85$), reinforcing its role in preventing osteoporosis and improving bone mineral density.

These statistical evaluations highlight that ragi not only possesses superior micronutrient density but also demonstrates consistent compositional reliability, making it an ideal candidate for nutritional interventions, especially in addressing calcium deficiency and malnutrition.

6.2. Statistical analysis of Pearl millet (Bajra) as a case study

Among various millets, pearl millet (*Pennisetum glaucum*; bajra) is the most widely consumed in India, accounting for approximately 40–45% of total millet production. Using the antioxidant data provided in the manuscript (Bello et al., 2022), a statistical evaluation can be demonstrated. For example, the mean antioxidant inhibition of pearl millet is reported as 44.910% with a standard deviation (SD) of ±3.597, while fonio millet shows 47.909% ± 3.472. The coefficient of variation (CV) for pearl millet is calculated as: CV = (SD / Mean) × 100 = (3.597 / 44.910) × 100 ≈ 8.01%,indicating moderate variability and reliability of antioxidant performance. A simple t-test comparison (assuming equal sample size, n=3) between pearl millet and fonio millet yields: $t \approx (47.909 - 44.910) / \sqrt{[(3.597^2/3) + (3.472^2/3)]} \approx 1.39$, suggesting that while fonio shows higher activity, the difference may not be statistically significant at $p < 0.05$. Such statistical tools: mean, standard deviation, coefficient of variation, and hypothesis testing are essential for validating experimental findings. Advanced tools like ANOVA, regression analysis, and principal component analysis (PCA) are widely recommended in food science research (Montgomery, 2017; Latimer, 2019, AOAC guidelines) to compare multiple millet varieties and bioactive components.

7. Conclusion

This thorough review highlights the substantial potential of millet as a nutritional powerhouse and a source of various pharmacological advantages. Millets provide a comprehensive mix of essential macronutrients and micronutrients, as well as bioactive compounds like phenolics and flavonoids, which enhance their antioxidant, anti-diabetic, anti-inflammatory, hypolipidemic, antimicrobial, neuroprotective, immunomodulatory, gastroprotective, and anticancer effects. Furthermore, their robustness and minimal resource needs make them viable options for global food security and enhanced dietary diversity. Future research should concentrate on enhancing cultivation and processing techniques, along with performing clinical trials to further authenticate and utilize the therapeutic potential of millet-derived compounds in addressing chronic diseases and supporting overall health.

CRediT statement

ASM: Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Data curation, Original draft preparation, Finalization of the manuscript and Visualization.

Declaration of competing interests

The authors declare that they have no known competing financial interests or personal relationships that could influence the work reported in this paper.

AI Disclosure Statement

During the preparation of this manuscript, the author used AI tools to improve the language and readability. After using this tool, the author reviewed the content and made changes wherever necessary. The author takes full responsibility for the contents of this publication.

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