**Review Article**

**Nutritional Composition and Health Advantages of Millets in Contemporary Dietary Practices – A Review**

**Abstract**

Millets are emerging as nutritionally dense and climate-resilient grsains capable of addressing the dual burden of malnutrition and sustainability in contemporary food systems. This review critically evaluates the nutritional composition, health benefits, and functional applications of millets, emphasizing their relevance in modern dietary practices. Millets such as finger millet, pearl millet, foxtail millet, and proso millet are rich in complex carbohydrates, dietary fibre, essential amino acids, vitamins (notably B-complex and E), and minerals like calcium, iron, magnesium, and zinc. Their low glycemic index, high antioxidant potential, and bioactive phytochemicals contribute to the prevention and management of non-communicable diseases including type 2 diabetes, cardiovascular disorders, obesity, and gastrointestinal ailments. Functional attributes such as immunomodulation, anti-inflammatory activity, and gut microbiota modulation further reinforce their therapeutic potential. The development of millet-based nutraceuticals, gluten-free formulations, and ready-to-eat products has expanded their application in health-oriented food markets. Despite these advantages, challenges remain in consumer acceptance, processing technology, and market access due to issues like coarse texture, taste preferences, and fragmented value chains. Strategic integration of millets into public nutrition programs, such as school feeding and maternal health schemes, along with targeted awareness campaigns, has demonstrated success in improving dietary diversity and micronutrient intake. Research efforts in biofortification, hybridization, and nutrigenomics are enhancing the nutritional profile and adaptability of millets under diverse agroecological conditions. Future directions should focus on clinical validation of health claims through controlled trials and the implementation of sustainable supply chain models to ensure equitable access. The findings underscore the potential of millets to serve as cornerstone crops for achieving food and nutritional security, especially under climate variability and rising health concerns. Comprehensive efforts combining science, policy, and consumer engagement are essential for mainstreaming millets into daily diets and global nutrition strategies.

**Keywords:** *Millets, Nutrition, Glycaemic, Biofortification, Antioxidants, Functional foods, Sustainability*

**I. Introduction**

*A. Global nutrition challenges and shifting dietary patterns*
Malnutrition in all its formsundernutrition, micronutrient deficiencies, overweight, and obesitycontinues to be a major global public health issue (Eiden *et.al.,* 2016). As per the FAO, over 2.4 billion individuals face moderate to severe food insecurity, and about 45 million children under five suffer from wasting. Modern dietary patterns, dominated by polished rice and refined wheat, have led to high glycemic loads and lower dietary fiber intake, contributing to a surge in non-communicable diseases (NCDs) like diabetes, cardiovascular disorders, and certain cancers. The increasing reliance on ultra-processed foods, characterized by high sugar, fat, and salt content, exacerbates nutritional imbalances and diet-related morbidities. Diversification of cereal intake by incorporating nutrient-dense, underutilized grains like millets is emerging as a strategic solution to address both macro and micronutrient deficiencies while reducing dependence on staple monocultures and promoting dietary sustainability.

*B. Historical and cultural importance of millets in human diets*
Millets were among the earliest cultivated crops, with archaeological records indicating their domestication as early as 3000–2500 BCE in the Indus Valley and parts of East Asia (Pokharia *et.al.,* 2014). These grains played a central role in traditional food systems across Africa and Asia, serving as staple dietary components before the Green Revolution era. Millets such as foxtail, finger, and pearl millet were widely consumed in semi-arid regions due to their drought resilience and minimal input requirements. Culinary traditions such as fermented millet porridges, steamed dumplings, and unleavened flatbreads highlight their rich ethnobotanical relevance. Over time, socio-economic transitions and aggressive promotion of polished cereals contributed to a gradual decline in millet consumption. Despite this shift, millet-based recipes and ceremonial use continue to reflect their deep cultural embeddedness across multiple agro-ecological landscapes.

*C. Objectives and scope of the review*
This review aims to systematically evaluate the nutritional composition and health advantages of millets with a focus on their role in contemporary dietary practices. It explores their macro- and micronutrient profiles, bioactive compounds, and therapeutic potential against NCDs. The review also examines millet-based functional food innovations, compares their nutritional metrics with commonly consumed cereals, and discusses challenges related to consumption and policy-level integration. Emphasis is placed on understanding how millets can support sustainable dietary transitions, food security, and global nutrition targets. The review draws upon peer-reviewed literature, governmental databases, and recent clinical and epidemiological studies to provide a comprehensive and evidence-based analysis.

**II. Millet Species and Classification**

*A. Major and minor millets: Finger millet, Pearl millet, Foxtail millet, Kodo millet, Barnyard millet, Little millet, Proso millet*
Millets represent a diverse group of small-seeded grasses grown primarily in arid and semi-arid regions (Nagaraja *et.al.,* 2024). They are broadly categorized as major and minor millets based on their area of cultivation and economic prominence. Major millets include Finger millet (Eleusine coracana) and Pearl millet (Pennisetum glaucum). Finger millet is a staple cereal rich in calcium and dietary fibre, commonly consumed in parts of Asia and Africa. Pearl millet, widely cultivated for its high drought tolerance, contains notable levels of iron, zinc, and protein. Minor millets encompass Foxtail millet (Setaria italica), Kodo millet (Paspalum scrobiculatum), Barnyard millet (Echinochloa spp.), Little millet (Panicum sumatrense), and Proso millet (Panicum miliaceum). These grains are valued for their high antioxidant capacity, low glycemic index, and dense nutritional profiles. The protein content of millets varies from 7% to 13%, and many minor millets contain higher dietary fiber (up to 18%) compared to traditional cereals. Their ability to grow in marginal soils under minimal input conditions has led to their identification as "climate-smart crops" by agricultural research organizations.

*B. Botanical classification and geographical distribution*
Millets belong to the Poaceae family, subfamily Panicoideae (Nie *et.al.,* 2018). Each species is taxonomically distinct yet shares common features such as C4 photosynthesis and resilience to abiotic stresses. Pearl millet (Pennisetum glaucum) is native to the Sahelian region of Africa and is cultivated extensively across arid zones. Finger millet (Eleusine coracana) has its origin in the Ethiopian highlands and was later disseminated to other tropical regions. Foxtail millet (Setaria italica) is one of the oldest domesticated millets, with origins traced to northern China around 6000 BCE. Kodo millet (Paspalum scrobiculatum) and Little millet (Panicum sumatrense) are largely cultivated in rainfed zones of South and Southeast Asia. Proso millet (Panicum miliaceum) has Eurasian origins and is adapted to temperate climates. Barnyard millet (Echinochloa frumentacea and E. esculenta) is known for rapid growth and short duration, often grown as a catch crop (Maithani *et.al.,* 2023). Millets are cultivated in more than 40 countries across Asia, Africa, and parts of Europe, covering over 30 million hectares globally.

*C. Agroecological adaptability and climate resilience*
Millets are inherently suited to diverse agroecological zones due to their deep root systems, efficient water-use physiology, and C4 photosynthetic pathway, which contributes to higher biomass production under high-temperature conditions. They exhibit substantial tolerance to drought, salinity, and poor soil fertility, making them ideal crops for climate-vulnerable and resource-poor farming systems. Their short growth cycles (60–100 days), low input requirements, and resistance to pests and diseases make them ecologically sustainable. Several millets, including finger and pearl millet, can be cultivated on marginal lands with annual rainfall as low as 300 mm, unlike rice and wheat that require over 1200 mm. Their cultivation not only ensures food security in water-scarce zones but also enhances soil carbon sequestration and biodiversity in cropping systems. The resurgence of millets in global policy dialogues stems from their critical role in combating climate change and malnutrition simultaneously.

**III. Nutritional Composition of Millets**

*A. Macronutrient profile*

*1. Carbohydrates and dietary fibers*
Millets are predominantly composed of complex carbohydrates, making them a valuable energy source for staple diets (Kumar *et.al.,* 2023). The carbohydrate content ranges from 60% to 72%, with significant proportions of slowly digestible starch (SDS) and resistant starch (RS), contributing to a low glycemic index (GI). Finger millet contains approximately 72% carbohydrates, with a notable fraction of dietary fiber, especially insoluble fiber, enhancing satiety and glycemic control. The total dietary fiber content in millets is significantly higher than that of polished rice or refined wheat, averaging 8.5%–12.5% across species, compared to 2%–3% in conventional cereals. Foxtail millet has one of the highest levels of insoluble fiber, improving bowel health and reducing the risk of colon cancer.

*2. Protein content and amino acid profile*
Millets provide moderate amounts of protein, typically ranging from 7% to 13%, varying by species (Saleh *et.al.,* 2013). Pearl millet contains up to 11.8% protein, while finger millet has around 7.3%. Though not complete proteins, millets are rich in sulfur-containing amino acids like methionine and cysteine, which are limiting in rice and wheat. Proso millet and foxtail millet demonstrate superior lysine levels compared to most cereals, addressing amino acid imbalances in vegetarian diets. The protein digestibility corrected amino acid score (PDCAAS) of millets is relatively moderate but can be enhanced through fermentation and sprouting.

*3. Lipid composition and fatty acid diversity*
Millets have a lipid content between 3% and 6%, higher than many traditional cereals (Kaur *et.al.,* 2019). Pearl millet contains up to 5.1% fat, including essential fatty acids such as linoleic and oleic acids. These unsaturated fats contribute to cardiovascular health and help in the absorption of fat-soluble vitamins. Finger millet and foxtail millet are low in saturated fat and contain phospholipids and glycolipids, beneficial for cellular structure and function. Their lipid profile contributes to their role in dietary management of lipid disorders and inflammation.

*B. Micronutrient richness*

*1. Vitamins (B-complex, E, A)*
Millets are rich in B-complex vitamins, especially niacin (vitamin B3), thiamine (vitamin B1), riboflavin (vitamin B2), and pyridoxine (vitamin B6), which play vital roles in energy metabolism and neurological function (Sonawane *et.al.,* 2024). Pearl millet contains about 4.2 mg of niacin per 100g, contributing significantly to recommended dietary allowances (RDAs). Foxtail and little millet also contain moderate levels of folic acid, essential during pregnancy for neural development. Tocopherols (vitamin E) present in millet lipids offer antioxidant protection, while carotenoids (provitamin A) in yellow cultivars of pearl and proso millet contribute to eye health.

*2. Minerals (Iron, Calcium, Zinc, Magnesium, Phosphorus)*
Millets are a dense source of essential minerals. Finger millet is the richest natural source of calcium among cereals, with levels ranging from 344 to 364 mg per 100g, compared to 10–20 mg in rice or maize. Pearl millet provides 8–10 mg of iron per 100g, helping alleviate anemia. Zinc content in proso millet (~2.9 mg/100g) and magnesium levels in foxtail millet (~114 mg/100g) aid in immune function and enzymatic regulation. Phosphorus content, vital for bone and cellular function, is substantial across all millet species, averaging around 220–280 mg/100g.

*C. Phytochemical and antioxidant properties*

*1. Polyphenols, flavonoids, tannins*
Millets contain significant amounts of bioactive phytochemicals that impart both antioxidant and anti-inflammatory properties (Shah *et.al.,* 2021). Finger millet is particularly high in ferulic acid, catechins, and tannins, which have shown potential in reducing oxidative stress markers. Proso and foxtail millets are rich in flavonoids like quercetin and kaempferol, associated with anti-carcinogenic and anti-diabetic effects. The presence of phytic acid and tannins, though considered antinutrients, can offer benefits such as chelation of excess iron and modulation of blood glucose response.

*2. Antioxidant activity and free radical scavenging potential*
Millet polyphenols exhibit high radical scavenging activity, as demonstrated by DPPH and FRAP assays. Finger millet showed 2–3 times higher total antioxidant capacity than rice and wheat when measured by ORAC values. Their ability to neutralize reactive oxygen species (ROS) contributes to reduced risk of chronic diseases such as type 2 diabetes, neurodegenerative disorders, and cardiovascular diseases. Processing techniques like germination, roasting, and fermentation enhance antioxidant bioavailability by reducing bound phenolic forms.

**IV. Comparative Nutritional Evaluation of Millets vs. Major Cereals**

*A. Nutrient density index comparison*
Millets outperform several major cereals like rice and wheat in terms of nutrient density, offering higher concentrations of essential minerals, vitamins, and bioactive compounds (Saleh *et.al.,* 2013). The Nutrient Density Index (NDI), which evaluates nutrient content per 100 kcal, highlights millets as superior in delivering nutrition per unit of energy. For instance, finger millet provides approximately 364 mg of calcium per 100g, which is nearly 10 times higher than that of rice (10 mg/100g) and wheat (30 mg/100g). Pearl millet contains about 8–10 mg of iron per 100g, compared to 0.4 mg in rice and 3.9 mg in wheat, aiding in addressing iron-deficiency anemia. The protein content in pearl millet (11.8%) and proso millet (12.5%) is comparable or higher than wheat (11.1%) and significantly higher than rice (6.8%). Proso millet also contains more niacin (4.5 mg/100g) than rice (1.9 mg/100g), enhancing its value in preventing pellagra and supporting neurological health. The high fiber content in millets (8.5–12.5%) contributes substantially to digestive health compared to rice (0.2–0.5%) and wheat (2%). These metrics reflect that millets contribute a broader spectrum of nutrients, particularly beneficial for low-calorie, nutrient-rich diets.

*B. Glycemic index and satiety values*
The glycemic index (GI) of a food item measures how quickly it raises blood glucose levels post-consumption (Saidaiah *et.al.,* 2024). Most millets have low to medium GI values, making them ideal for glycemic control. Foxtail millet and little millet have GI values ranging from 40 to 50, significantly lower than white rice (GI = 72–89) and wheat (GI = 60–69). Finger millet, despite its relatively higher carbohydrate content, has a GI of 65 due to its high fiber and polyphenol composition, which modulate glucose absorption. The slow-release carbohydrates in millets contribute to lower postprandial blood sugar spikes, especially beneficial for type 2 diabetic populations. Satiety values are also higher in millets due to their bulk-forming fiber and protein content, reducing subsequent calorie intake and assisting in weight management. A controlled intervention study demonstrated that replacing refined cereals with millets in daily meals led to improved satiety and reduced hunger pangs over a 12-week period.

*C. Functional nutrition assessment*
Functional nutrition emphasizes not just caloric intake but how specific nutrients and compounds affect metabolic and disease-preventive functions (Paliyath *et.al.,* 2011). Millets are a potent source of functional bioactive compounds, including ferulic acid, phytic acid, and flavonoids, which offer antioxidant, antimicrobial, and anti-inflammatory benefits. In contrast, major cereals like polished rice lose significant micronutrients during milling and offer fewer health-promoting phytochemicals. The functional score for millets is elevated by their effect on metabolic syndrome parameters—lowering blood pressure, improving lipid profiles, and enhancing insulin sensitivity. Pearl millet supplementation in a study reduced LDL cholesterol and fasting glucose in prediabetic adults. Moreover, the naturally gluten-free nature of millets such as sorghum, proso, and foxtail millet positions them as suitable for gluten-intolerant individuals and celiac patients. The presence of resistant starch and prebiotic fibers also supports beneficial gut microbiota, strengthening systemic immunity and digestive function (Liu *et.al.,* 2020).

**V. Health Advantages of Millets in Modern Diets**

*A. Role in non-communicable disease prevention*

*1. Diabetes and glycemic control*
Millets play a crucial role in managing type 2 diabetes through their low glycemic index (GI) and high dietary fiber content. Finger millet (Eleusine coracana), foxtail millet (Setaria italica), and little millet (Panicum sumatrense) have GI values between 40 and 50, compared to 72–89 for white rice and 60–69 for refined wheat. This slower carbohydrate digestion leads to controlled postprandial glucose levels. In a meta-analysis, millet-based diets significantly reduced fasting blood glucose and improved insulin sensitivity. Controlled trials involving finger millet consumption showed HbA1c reduction in prediabetic patients over 3 months. The resistant starch and polyphenols present in millets, particularly ferulic acid and catechins, modulate insulin activity and reduce oxidative stress, contributing to improved glycemic control (Bhujle *et.al.,* 2025).

*2. Cardiovascular health and cholesterol modulation*
Regular inclusion of millets has shown beneficial effects on lipid metabolism and cardiovascular biomarkers. Pearl millet (Pennisetum glaucum) and foxtail millet contain high levels of magnesium (114 mg/100g) and potassium, essential for vasodilation and blood pressure regulation. Beta-glucans and insoluble fibers in these grains reduce LDL cholesterol absorption by binding bile acids. A study demonstrated that foxtail millet consumption led to a significant decrease in total cholesterol and LDL levels in hyperlipidemic adults. Flavonoids such as quercetin and tricin exhibit anti-atherosclerotic properties by inhibiting lipid peroxidation and improving endothelial function (Barnaba *et.al.,* 2019).These attributes align millets with therapeutic dietary strategies for coronary heart disease prevention.

*3. Obesity and weight management*
The high fiber content and bulk-forming properties of millets support appetite regulation and satiety enhancement. Millets contain between 8.5% and 12.5% dietary fiber, which increases mastication time, delays gastric emptying, and stimulates satiety hormones such as GLP-1 and PYY. Controlled feeding trials indicated that proso millet and barnyard millet consumption resulted in reduced body mass index (BMI) and waist circumference among overweight individuals over a 12-week intervention. The low energy density of millets supports caloric restriction without compromising nutrient intake, making them ideal for sustainable weight management diets. Their slowly digestible starches and higher protein levels contribute to thermogenic effects that promote metabolic efficiency.

*B. Gastrointestinal and gut microbiome benefits*
Millets serve as prebiotic substrates that nourish beneficial gut microbiota such as *Lactobacillus* and *Bifidobacterium* (Singh *et.al.,* 2023). Their insoluble fibers, arabinoxylans, and resistant starches facilitate fermentation in the colon, leading to the production of short-chain fatty acids (SCFAs), which enhance colonic health and barrier integrity. Fermented millet-based foods increase bioavailability of nutrients and promote probiotic activity. Studies on foxtail millet-based synbiotic formulations reported a rise in fecal SCFA concentrations and microbial diversity indices. This gut modulation has systemic implications, including improved glucose metabolism, reduced intestinal inflammation, and enhanced immune function.

*C. Bone health and mineral bioavailability*
Finger millet is exceptionally rich in calcium, offering 344–364 mg/100g, which is ten times higher than rice and nearly five times higher than wheat (Tamilselvan *et.al.,* 2023). Calcium, phosphorus, and magnesium in millets synergistically contribute to bone mineral density, skeletal growth, and osteoblast function. Phytates and tannins can bind these minerals, reducing their bioavailability, but this effect can be minimized by traditional processing methods like soaking, fermentation, and germination. Intervention studies revealed that regular intake of finger millet-based meals improved serum calcium and bone turnover markers in adolescent girls and postmenopausal women. The natural magnesium content supports bone matrix formation and inhibits bone resorption, reducing osteoporosis risk.

*D. Immunomodulatory and anti-inflammatory effects*
Millets contain a variety of bioactive compounds, including lignans, phytic acid, and flavonoids, that influence immune responses and inflammatory pathways (Shukla *et.al.,* 2024). Polyphenols like ferulic acid and tannins from finger millet and sorghum modulate cytokine production, particularly by suppressing pro-inflammatory markers such as TNF-α, IL-6, and CRP. These compounds also act as antioxidants, neutralizing reactive oxygen species (ROS) that damage immune cells and promote chronic inflammation. In vivo studies using millet-based diets demonstrated enhanced macrophage phagocytic activity and increased immunoglobulin levels. Regular millet consumption may thus play a role in managing conditions associated with low-grade inflammation, including metabolic syndrome and autoimmune disorders.

**VI. Functional and Therapeutic Foods from Millets**

*A. Development of millet-based nutraceuticals*
Millets serve as a foundational ingredient in the development of nutraceutical products owing to their dense composition of bioactive compounds such as polyphenols, dietary fiber, flavonoids, lignans, and resistant starch (Tripathi *et.al.,* 2021). These compounds impart health-promoting properties, particularly targeting metabolic disorders, oxidative stress, and inflammatory diseases. Finger millet (Eleusine coracana) contains high levels of ferulic acid and catechins that have demonstrated antidiabetic and cardioprotective effects in vitro and in vivo studies. Pearl millet (Pennisetum glaucum) has been explored for its potential in managing hyperlipidemia, supported by its phytosterol and saponin content which inhibit cholesterol absorption. Nutraceutical formulations derived from millets include antioxidant-rich millet flakes, high-fiber cookies, and protein-fortified breakfast cereals. Recent R&D has focused on millet-based synbiotic formulations combining prebiotics and probiotics to enhance gut health, particularly using foxtail and barnyard millet matrices. Millet-derived nutraceuticals have gained recognition for their role in delaying the onset of non-communicable diseases while improving immune function and oxidative balance (Pudake *et.al.,* 2023).

*B. Millet incorporation in gluten-free and allergen-free diets*
Millets are naturally gluten-free and are excellent dietary alternatives for individuals suffering from celiac disease, non-celiac gluten sensitivity, or wheat allergy (Asrani *et.al.,* 2023). Sorghum, finger millet, and proso millet have been incorporated into gluten-free flours and bakery mixes without compromising nutritional value or sensory attributes. These grains offer significantly more micronutrients such as iron, magnesium, and B-complex vitamins than typical gluten-free staples like corn or rice. Their inclusion in specialized diets is supported by low allergenicity, hypoallergenic profiles, and favorable digestibility. Clinical assessments reveal that millet-based diets reduce gastrointestinal inflammation and improve villous architecture in gluten-sensitive patients. Millet flour has been utilized in the preparation of allergen-free pastas, flatbreads, and ready-to-eat snacks that are both nutritionally dense and functionally viable for long-term therapeutic use. Sorghum flour enriched with chia or flaxseed, as part of an elimination diet, has shown improvements in skin sensitivity and systemic inflammation among pediatric allergy cohorts.

*C. Formulated health beverages, bars, and supplements*
Millets have become central to the innovation of functional beverages and food supplements due to their antioxidant-rich composition and bioavailable micronutrients (Dhiman *et.al.,* 2024). Fermented millet-based drinks such as kanji (using finger millet) and probiotic-enriched foxtail millet smoothies are gaining commercial popularity for their gut microbiome support and detoxification potential. These drinks provide a natural source of polyphenols, vitamin E, and B-complex vitamins, which contribute to enhanced metabolic function and immunity. Millet-based nutrition bars, often incorporating nuts, seeds, and dried fruits, offer a balanced macronutrient profile ideal for sports and diabetic nutrition. Barnyard millet and kodo millet flours are being integrated into energy bar formulations due to their high fiber and mineral content. Supplements using encapsulated millet polyphenols, especially finger millet-based calcium and iron tablets, are under evaluation for use in maternal and child health programs. Technological innovations, including spray drying and microencapsulation, are improving the shelf life and bioefficacy of these formulations, making millets an ideal platform for therapeutic food development.

**VII. Millet Value Addition, Processing, and Nutritional Retention**

*A. Traditional and modern processing techniques*
Millets have been processed using both traditional and modern techniques to improve palatability, shelf life, and nutritional quality (Mahajan *et.al.,* 2024). Traditional processing methods include dehulling, soaking, roasting, malting, fermentation, and grinding, which help reduce antinutritional factors and enhance sensory acceptability. Roasting enhances aroma and reduces moisture content, thereby extending storage stability. Soaking and sun-drying are commonly employed to initiate enzymatic changes that improve digestibility.Modern processing techniques such as extrusion cooking, microwave drying, infrared heating, spray drying, and vacuum packaging are increasingly used to manufacture ready-to-eat and ready-to-cook millet products. Extrusion, for example, improves protein digestibility and starch gelatinization while reducing bulk density, making products more suitable for infant and geriatric consumption (Alam *et.al.,* 2016). Roller milling and parboiling enhance the recovery of fine flour and reduce cooking time. Pre-treatment technologies like high-pressure processing (HPP) and pulsed electric field (PEF) are gaining attention for their ability to inactivate microbes and enzymes without significant nutrient loss. These processing strategies have enabled the formulation of a wide range of value-added millet products such as flakes, pasta, vermicelli, breakfast cereals, snacks, and baking flour blends.

*B. Impact of decortication, fermentation, germination on nutrient bioavailability*
Decortication or dehulling involves the removal of the outer husk, improving cooking quality and appearance but leading to a reduction in fiber, phenolic compounds, and some minerals, particularly iron and zinc located in the bran layer (Sruthi *et.al.,* 2021). The degree of nutrient loss depends on the extent of milling; moderate decortication retains more bioactive compounds while improving digestibility. Fermentation is a biological process that improves bioavailability of minerals, particularly iron, calcium, and zinc, by degrading phytic acid and releasing bound micronutrients. Lactic acid fermentation using *Lactobacillus plantarum* and *Pediococcuspentosaceus* enhances organoleptic properties and reduces tannins, thereby improving protein digestibility and sensory appeal. Traditional fermented millet products such as ambali, dosa, idli, and kanji have shown increased nutrient retention and probiotic enrichment.Germination activates endogenous enzymes like phytase and amylase, reducing antinutritional factors and increasing levels of bioactive compounds. Germinated finger millet has shown a 30–50% increase in γ-aminobutyric acid (GABA) and enhanced calcium bioavailability. Sprouted millet flours are being utilized in the development of weaning foods and therapeutic formulations targeting anemia and stunting. Processing combinations, such as fermentation followed by drying, maximize both shelf stability and nutritional gains.

*C. Development of millet-based functional food products*
Value addition has expanded the utility of millets into a wide array of functional foods that address both nutritional deficiencies and lifestyle diseases (Dhaka *et.al.,* 2021). Products such as multi-grain health bars, protein-rich granola, iron-fortified porridge mixes, and gluten-free bakery items are being commercially produced using finger, pearl, foxtail, and proso millets. Ready-to-eat snacks like popped millet puffs and baked crisps combine high fiber and antioxidant activity with consumer appeal.Research and development in food technology have led to the innovation of millet-based probiotic yogurt, low-GI noodles, and instant soup powders, which are tailored to meet specific dietary requirements of diabetic, cardiovascular, and gluten-sensitive populations. Millet inclusion in school meal programs, hospital diets, and nutrition rehabilitation centers has shown improvements in growth markers and cognitive performance in children. Functional fortification with iron, folic acid, vitamin B12, and omega-3 fatty acids is being applied to millet-based food matrices to enhance their therapeutic potential. Spray drying and encapsulation technologies are used to deliver heat-sensitive micronutrients without degradation. The commercialization of such products is supported by consumer demand for clean-label, high-fiber, and minimally processed food solutions (Polachini *et.al.,* 2023).

**VIII. Consumer Trends and Market Demand for Millets**

*A. Shifting consumer preferences towards plant-based, whole grain diets*
A growing segment of global consumers is transitioning toward plant-based and whole grain diets driven by health, sustainability, and ethical considerations (Vinnari *et.al.,* 2014). Millets, with their high dietary fiber, low glycemic index, and abundance of micronutrients, align with these preferences. The global whole grain food market is expanding at a compound annual growth rate (CAGR) of 6.4%, reflecting rising awareness about the health benefits of fiber-rich diets. Millets offer a compelling alternative to refined cereals, being naturally gluten-free, rich in antioxidants, and capable of reducing the risk of lifestyle diseases. Their suitability in vegan and clean-label food formulations enhances their attractiveness among health-conscious and urban populations seeking minimally processed, nutrient-dense staples.

*B. Millet branding, commercialization, and market trends*
The global millet market is witnessing consistent growth. Reports estimate the market value ranging from USD 14.2 billion to USD 36.9 billion in 2023, with projections reaching USD 55.7 billion by 2030 at a CAGR of 4.4%–6.2% (Pascale *et.al.,* 2021). This surge is driven by the demand for functional foods, gluten-free alternatives, and ethnic grain-based innovations. Major food manufacturers and startups are increasingly incorporating millets into ready-to-eat snacks, breakfast cereals, health bars, and bakery products. Millet-based product segments are expected to double in value over the next decade, particularly in Asia-Pacific, North America, and Europe. Branding strategies now focus on sustainability, climate resilience, and traditional grain revival, supported by consumer interest in heritage foods. The market trajectory suggests that millets are no longer niche but part of mainstream dietary trends.

*C. Public health policy and millet promotion campaigns*
Policy interventions and awareness campaigns are significantly shaping millet demand (Singh *et.al.,* 2023).The declaration of 2023 as the International Year of Millets by the United Nations catalyzed global momentum through government-led programs, research collaborations, and marketing initiatives. The Smart Food campaign by ICRISAT has advanced millet mainstreaming through food contests, recipe innovations, and school interventions. Denmark’s national whole grain initiative demonstrated the effectiveness of coordinated efforts; daily consumption rose from 36 g to 82 g over a decade through clear labeling and public-private alliances. Similar frameworks could be adapted to increase millet consumption globally. Surveys indicate that while health-conscious consumers are inclined toward millets, awareness remains limited, and taste perceptions, price disparities, and supply chain gaps hinder large-scale adoption. Experts highlight the need for stable procurement policies, price incentives, and millet inclusion in welfare programs to ensure equitable access and farmer profitability.

**IX. Challenges and Barriers in Millet Integration into Daily Diets**

*A. Post-harvest and processing constraints*
One of the major limitations hindering millet consumption is the lack of standardized and efficient post-harvest handling systems (Dinesh *et.al.,* 2025). Millets are small-grained and encased in hard outer husks, which makes dehuskinglabour-intensive and time-consuming. Mechanical threshers and dehullers used for rice or wheat are not compatible with most millet varieties. Inefficient processing often leads to grain breakage, nutrient loss, and reduced shelf life. Manual processing not only increases drudgery but also discourages large-scale adoption. Moreover, lack of modern processing units limits the production of ready-to-cook or ready-to-eat millet products. The nutritional degradation of millets during excessive polishing or heat treatment also remains a critical concern. Losses in essential micronutrients, such as iron and calcium, have been observed in over-milled millet flours, reducing their functional value. These constraints require investment in millet-specific processing technologies that retain nutrient density while enhancing consumer appeal.

*B. Taste, texture, and cultural preferences*
Millets exhibit unique organoleptic properties that can be unfamiliar or undesirable to consumers accustomed to polished rice and refined wheat (Mishra *et.al.,* 2024). The coarse texture, earthy flavour, and dryness associated with cooked millet dishes often deter regular consumption, particularly among younger populations. Survey data from metropolitan regions revealed that 91% of participants considered taste a significant barrier to adopting millet-based foods, while 68% preferred softer and more neutral cereals. Cooking millets also requires more time and water management, which is a practical deterrent in urban fast-paced lifestyles. In many communities, millets are historically perceived as food for the economically disadvantaged, a stigma that persists and impacts consumption trends. This cultural perception undermines consumer willingness to pay premium prices for millet-based health foods, despite awareness of their nutritional superiority. Bridging this gap requires recipe innovations, culinary rebranding, and aggressive awareness campaigns focused on taste improvement and health appeal.

*C. Supply chain, storage, and marketing issues*
Millet supply chains remain fragmented with limited integration between producers, processors, and retailers (Pandey *et.al.,* 2023). Farmers face challenges in accessing quality seeds, input support, and market linkages. As a result, production remains inconsistent, and market volumes are insufficient to support sustained commercial scaling. Moreover, millets have shorter shelf life due to higher fat content, which leads to rancidity under suboptimal storage conditions. Storage infrastructure, such as silos and cold chains, remains largely unavailable for small millet farmers, increasing post-harvest losses by up to 30%. Marketing barriers are compounded by limited millet representation in public distribution systems, school feeding schemes, and urban retail platforms. While demand for health foods is rising, millet products are often priced higher due to low economies of scale, making them less accessible to middle- and low-income groups. Visibility of millets in mainstream supermarkets and e-commerce platforms remains poor, and there is a lack of consistent branding or labelling standards to distinguish high-quality millet products. Addressing these structural gaps requires coordinated policy support, farmer cooperatives, and private sector participation to streamline supply chains and promote millet availability across consumer segments (Khushwaha *et.al.,* 2023).

**X. Strategies to Promote Millet Consumption in Contemporary Diets**

*A. Public nutrition and awareness campaigns*
Awareness campaigns play a pivotal role in reshaping dietary behaviour and promoting millets as a health-forward food choice. Initiatives like the Smart Food Campaign by ICRISAT have been instrumental in highlighting millets as “good for you, the planet, and the farmer” through educational outreach, media engagement, and culinary contests. Digital and print campaigns supported by the Food and Agriculture Organization (FAO) during the International Year of Millets 2023 helped communicate the nutritional and ecological advantages of millets globally. Consumer education programs focusing on the health benefits of millets, including their high dietary fibre, low glycemic index, and rich micronutrient content, have been shown to improve willingness to incorporate them into daily meals. Evidence suggests that multi-channel campaigns—combining schools, social media, local food fairs, and healthcare settings—can substantially improve awareness and uptake among both urban and rural populations (Yusriadi *et.al.,* 2024).

*B. Millet inclusion in national food programs and mid-day meals*
The integration of millets into institutional feeding schemes has shown promise in increasing both production and consumption (Tiwari *et.al.,* 2023). When included in school mid-day meals, fortified millet-based dishes improve nutritional status indicators such as hemoglobin levels, BMI, and cognitive scores in children. Millet-based hot meals in school programs provide a cost-effective and locally adaptable solution to address micronutrient deficiencies. Similarly, inclusion in the public distribution system and anganwadi nutrition programs can enhance dietary diversity among vulnerable populations. Pilot projects have demonstrated that finger millet-based meals contributed to a 12% reduction in anemia and improved attention span in primary school children over a 6-month period. The success of these programs depends on efficient procurement from local farmers, tailored recipes, and training of meal providers in millet preparation techniques.

*C. Research and development in millet biofortification and hybridization*
Scientific interventions are crucial to improving the nutritional density and agronomic traits of millets (Kudapa *et.al.,* 2023). Biofortification efforts led by organizations such as HarvestPlus and ICRISAT have successfully enhanced iron, zinc, and provitamin A content in pearl millet and finger millet. Genomic studies have identified candidate genes associated with nutrient accumulation and drought tolerance, aiding marker-assisted breeding. Hybrid varieties like ICTP-8203 have shown 60–70 ppm iron levels and 35% yield superiority compared to traditional landraces. Breeding programs now focus on reducing anti-nutritional factors (phytates, tannins) and enhancing protein digestibility. R&D is also advancing in the area of climate-resilient millet hybrids capable of tolerating extreme temperatures and erratic rainfall. Such innovations improve both farmer profitability and consumer acceptability, enabling millets to occupy a more prominent role in national food systems.

**XI. Future and Opportunities**

*A. Bioavailability and nutrigenomics of millet compounds*
Future research must focus on understanding the bioavailability of key nutrients in millets and their interaction with human genetics (Vinoth *et.al.,* 2017). While millets are rich in calcium, iron, zinc, and B-vitamins, their absorption is often limited by anti-nutritional compounds such as phytates and tannins. Investigating processing techniques like fermentation and germination that enhance mineral bioavailability is essential. Emerging nutrigenomic studies explore how individual genetic variations influence the response to millet-based diets. Identification of bioactive peptides and secondary metabolites from millets that regulate gene expression related to lipid metabolism, insulin sensitivity, and immune function presents new therapeutic possibilities. Integration of omics platformsgenomics, proteomics, metabolomicscan offer precision nutrition frameworks where millet intake is personalized for maximum health benefit.

*B. Millet-based dietary interventions and clinical trials*
Clinical validation of health claims related to millets is a crucial area for evidence-based policymaking and product development (Ghosh *et.al.,* 2023). Controlled dietary intervention trials have begun to assess the impact of millet consumption on metabolic syndrome, diabetes, cardiovascular diseases, and gut health. Daily consumption of finger millet reduced fasting glucose levels and HbA1c in type 2 diabetics. Trials in elderly populations show improved digestion, enhanced bowel regularity, and better lipid profiles with proso and barnyard millet diets. Longitudinal studies over multiple demographicsincluding children, pregnant women, and athletesare needed to quantify the health outcomes of millet intake. Double-blind, placebo-controlled trials assessing the efficacy of millet-based nutraceuticals and fortified foods will provide clinical legitimacy for future food innovations.

*C. Role in sustainable and climate-smart nutrition strategies*
Millets possess a low environmental footprint and are pivotal to developing climate-resilient food systems (Raut *et.al.,* 2023). Their ability to thrive in marginal soils, low water regimes, and under minimal agrochemical input make them ideal candidates for sustainable agriculture. Future research should evaluate the lifecycle impact of millet production, comparing water use, greenhouse gas emissions, and carbon sequestration potential with that of rice and wheat systems. Agronomic studies on intercropping millets with legumes and oilseeds can optimize soil health, biodiversity, and yield resilience. Diet modelling studies are required to incorporate millets into national dietary guidelines for reducing ecological pressure while meeting nutritional needs. Innovations in agroecological practices, value chains, and digital traceability systems will ensure that millet-based diets are not only healthy but also environmentally responsible and economically inclusive (Patil *et.al.,* 2023).

**XII. Conclusion**

Millets represent a nutritionally superior, climate-resilient grain group with immense potential to address modern dietary challenges, including nutrient deficiencies, non-communicable diseases, and environmental sustainability. Rich in dietary fibre, essential amino acids, minerals like calcium, iron, and zinc, and bioactive compounds such as polyphenols and flavonoids, millets offer multifaceted health benefits, including glycaemic control, improved lipid metabolism, and enhanced gut function. Advances in value addition, processing technologies, and functional food development have increased their appeal across consumer segments. Integration into public food systems, school meals, and biofortification initiatives has shown measurable improvements in nutritional outcomes. Despite these benefits, barriers such as poor post-harvest infrastructure, taste preferences, and limited market penetration persist.

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