**Millets in Modern Diets: A Comprehensive Review of Their Nutritional and Health Benefits**

**Abstract**

Millets are small-seeded, climate-resilient cereal crops that have gained increasing attention for their potential role in promoting sustainable agriculture and addressing global nutritional challenges. This review explores the comprehensive nutritional profile and documented health benefits of various millet species, including pearl millet (*Pennisetum glaucum*), finger millet (*Eleusine coracana*), foxtail millet (*Setaria italica*), and proso millet (*Panicum miliaceum*). Millets are rich in complex carbohydrates, dietary fibre, essential amino acids, unsaturated fatty acids, and micronutrients such as calcium, iron, magnesium, zinc, and B-complex vitamins. Their low glycemic index and high antioxidant content contribute to improved glycemic control, cardiovascular health, gastrointestinal function, and weight management. Bioactive compounds in millets, including phenolics and flavonoids, exhibit anti-inflammatory and antioxidant properties, further enhancing their therapeutic potential. As gluten-free grains, millets are also suitable for individuals with celiac disease or gluten intolerance. Traditional and modern processing methods, such as soaking, fermentation, puffing, and extrusion, play critical roles in improving the palatability, nutrient bioavailability, and shelf-life of millet-based foods. Despite their nutritional advantages, the widespread adoption of millets in modern diets is hindered by factors such as the presence of anti-nutritional compounds, limited consumer awareness, unfavourable taste preferences, and underdeveloped value chains. Policy interventions, public health advocacy, and food innovations are crucial to increasing millet consumption and positioning it as a functional food in global markets. Ongoing research into genetic improvement, biofortification, and clinical applications continues to unlock new opportunities for enhancing the nutritional and agronomic value of millets. With growing interest in sustainable and health-focused diets, millets offer a promising, underutilised solution to simultaneously combat chronic disease, malnutrition, and climate-induced agricultural challenges.

**Keywords:** *Millets, Nutritional profile, Glycemic index, Functional foods, Bioactive compounds, Sustainable agriculture, Chronic disease prevention*

**I. Introduction**

***A. Background on global dietary trends and health challenges***

Global dietary patterns have undergone a dramatic transformation over the past few decades, marked by a significant shift toward high-calorie, processed foods rich in refined sugars, saturated fats, and sodium. This phenomenon, often referred to as the "nutrition transition," has contributed to an alarming increase in non-communicable diseases (NCDs), including obesity, cardiovascular diseases, type 2 diabetes, and certain types of cancer. As of 2023, over 2.2 billion people globally are overweight or obese, and more than 463 million adults are living with diabetes.

These health issues are compounded by widespread micronutrient deficiencies, affecting an estimated two billion people worldwide. Iron-deficiency anaemia, vitamin A deficiency, and iodine deficiency are among the most prevalent forms of malnutrition (Mason et.al., 2005). Modern food systems often prioritise yield and convenience over nutrition and sustainability, resulting in monotonous diets dominated by staple crops like wheat, rice, and maize, which lack essential micronutrients and dietary diversity.

***B. Historical importance and cultural relevance of millets***

Millets are among the oldest cultivated grains, with archaeological evidence suggesting their domestication as early as 7000 BCE in regions of East Asia and Sub-Saharan Africa (Joshi *et.al.,* 2021). These grains are a diverse group of small-seeded grasses that have served as staple cereal crops in many parts of Asia and Africa for thousands of years. The major millets include finger millet, foxtail millet, pearl millet, proso millet, barnyard millet, little millet, and kodo millet. (Singh et al.,2023). Among these grains, pearl millet (*Pennisetum glaucum*), finger millet (*Eleusine coracana*), foxtail millet (*Setaria italica*), and proso millet (*Panicum miliaceum*), have traditionally been staple foods in many agrarian societies, valued for their resilience and adaptability to marginal conditions.

Millets hold deep cultural significance in many traditional societies, often associated with rituals, festivals, and local cuisines (Ankita *et.al.,* 2025). They have been integral to the dietary practices of indigenous populations and continue to be revered for their nutritional and medicinal properties in many folk traditions. These grains were once predominant in household consumption before being overshadowed by the Green Revolution's emphasis on rice and wheat.

***C. Rising interest in millets as sustainable, nutritious grains***

Global food policy experts and nutrition scientists are increasingly advocating for the reintroduction of millets into mainstream diets due to their numerous agronomic and health benefits. The year 2023 will be observed as the ‘Global Year of Millets’ because these millets are recognised as sustainable options for achieving food and nutritional security, garnering significant attention due to their health benefits and environmentally friendly characteristics (Sanjay et al.,2024). Millets are considered climate-smart crops because of their ability to thrive in arid environments, tolerate poor soils, and require minimal water and agrochemical inputs (Lenka *et.al.,* 2020). They have a lower carbon footprint compared to major cereals and play a crucial role in conserving agro-biodiversity.

From a nutritional standpoint, millets offer superior profiles compared to refined cereals. They are rich in complex carbohydrates, dietary fibre, essential amino acids, vitamins (particularly B-complex), and minerals such as iron, calcium, magnesium, and zinc. Their low glycemic index and high antioxidant content make them especially beneficial for managing diabetes, obesity, and cardiovascular conditions. Millets’ nutritional makeup and possible medical uses, adding to the expanding conversation on the inclusion of these grains in modern diets, again because of their positive effects on the environment and human health (Ankita & Seth,2025). Growing concerns over the sustainability of current food systems and the health implications of ultra-processed diets have spurred renewed research and investment in millet cultivation, product development, and public awareness campaigns (Capozzi *et.al.,* 2021).

***D. Purpose and scope of the review***

This review aims to consolidate and evaluate the existing scientific literature on the nutritional attributes and health-promoting properties of millets. By analysing data from clinical studies, nutritional assessments, and agricultural research, the paper highlights how millets can serve as a cornerstone for developing healthier, more sustainable diets.

The scope of this review encompasses a comprehensive exploration of millet types, their macronutrient and micronutrient content, bioactive compounds, processing methods, and documented health benefits. Special attention is given to their role in addressing metabolic disorders, digestive health, cardiovascular risk, and food security.

**II. Overview of Millets**

***A. Definition and classification***

Millets are a group of small-seeded grasses belonging to the family Poaceae, cultivated primarily for their grains, which are used in human food and animal feed (Mall *et.al.,* 2016). These cereals are often considered “nutri-cereals” because of their high nutritional value, particularly in terms of protein, dietary fibre, vitamins, and minerals. Millets are also recognised for their adaptability to harsh environmental conditions, including drought-prone and semi-arid regions, which makes them highly suitable for cultivation in areas with marginal soils and low rainfall.

The classification of millets typically falls into two categories based on grain size and cultivation volume (Naik *et.al.,* 2022). Major millets include species such as *Pennisetum glaucum* (pearl millet), *Eleusine coracana* (finger millet), and *Setaria italica* (foxtail millet). These grains are produced on a relatively large scale and form a staple food source in several regions. Minor millets, on the other hand, include *Panicum miliaceum* (proso millet), *Paspalum scrobiculatum* (kodo millet), *Echinochloa frumentacea* (barnyard millet), *Panicum sumatrense* (little millet), and *Brachiaria ramosa* (browntop millet), which are cultivated on a smaller scale but possess equally significant nutritional and ecological benefits.

***1. Major vs. minor millets***

The distinction between major and minor millets is not a reflection of their nutritional or agronomic importance but rather the scale and extent of their cultivation (Singh *et.al.,* 2020). Major millets are typically more prominent in agricultural policy and food systems due to higher yield volumes and widespread usage. Pearl millet, for instance, is one of the most drought-tolerant cereal crops and contributes significantly to food security in arid zones. Finger millet is valued for its exceptional calcium content and long shelf life, while foxtail millet is known for its short growing period and high iron levels. Minor millets, despite their lower production scale, are rich in polyphenols, antioxidants, and essential nutrients, and are increasingly recognised for their role in climate-resilient agriculture and nutrition-sensitive diets.

***2. Common types: Pearl millet, Finger millet, Foxtail millet, Proso millet, etc.***

Pearl millet (*Pennisetum glaucum*) is among the most widely cultivated millet species and is known for its high iron content, which can range from 6 to 8 mg per 100 grams, along with a protein content of 10 to 12% (Tako *et.al.,* 2015). It is resilient to both drought and heat stress, making it a staple in many arid zones. Finger millet (*Eleusine coracana*) stands out for its extraordinary calcium concentration, averaging 344 mg per 100 grams—more than ten times the calcium found in rice or wheat. This makes it particularly important for bone health and child nutrition. Foxtail millet (*Setaria italica*) contains approximately 12.3% protein and 8% dietary fibre, with a high proportion of slowly digestible starch, contributing to its low glycemic index and utility in managing metabolic disorders. Proso millet (*Panicum miliaceum*) matures quickly and is well-suited to areas with limited rainfall. It provides about 12.5% protein and contains significant levels of phenolic compounds with antioxidant properties.

These diverse millet species collectively contribute to dietary diversification, nutritional adequacy, and ecological sustainability, making them essential components in efforts to build resilient food systems.

***B. Global distribution and cultivation***

Millets are cultivated across more than 40 countries, primarily within Asia and Sub-Saharan Africa, as well as in parts of Europe and North America (Saxena *et.al.,* 2018). Globally, the total area under millet cultivation reached nearly 30 million hectares in 2021, with an estimated annual production of approximately 30 million metric tonnes. Their prominence in semi-arid and arid regions is due to their ability to grow under low-moisture and low-fertility conditions, which positions them as ideal crops for addressing food security challenges under climate stress.

Africa contributes the largest share of global millet production, accounting for nearly 55% of the total. Countries such as Niger, Nigeria, Mali, and Sudan are significant producers of pearl millet, which serves as a staple cereal in both rural and urban diets. Asia follows with around 35% of global millet production. China is one of the largest producers of foxtail millet, while Nepal and Sri Lanka cultivate finger millet and other local varieties. Europe and North America represent smaller production zones where millets are primarily grown for niche health markets, bird feed, and rotational forage crops.

The strategic cultivation of millets is increasingly seen as a way to diversify cropping systems and mitigate the risks of climate variability (Haussmann *et.al.,* 2012). Their short growing season, minimal irrigation requirements, and adaptability to degraded soils contribute to their importance in ensuring sustainable agricultural development.

***C. Agricultural and environmental benefits***

***1. Climate resilience***

Millets are uniquely adapted to withstand extreme climatic conditions. Most millet species require less than 500 mm of rainfall annually and can grow in temperatures exceeding 40°C, making them far more tolerant to drought and heat than wheat or rice (Saxena *et.al.,* 2018). Their ability to perform well under environmental stress has made them central to climate-resilient farming strategies, particularly in dryland agriculture.

***2. Low input requirements***

Compared to major cereals, millets require significantly lower inputs in terms of water, synthetic fertilisers, and pesticides. They thrive in low-fertility soils and often require no irrigation, depending primarily on rain-fed conditions. Studies have shown that millet cultivation uses 70% less water than rice and 40% less than wheat, which makes them highly suitable for sustainable farming in water-scarce regions. This low-input nature not only reduces production costs but also minimises the environmental footprint of agriculture.

***3. Role in sustainable agriculture***

Millets contribute substantially to sustainable agricultural systems through multiple pathways (Choudhary *et.al.,* 2023). Their ability to grow in marginal lands and underutilised agroecological zones helps reduce land degradation and promotes biodiversity. Millets also support crop diversification, enhancing soil fertility and reducing the risk of total crop failure during climatic shocks. As part of traditional intercropping systems, millets have been associated with improved pest control and reduced dependence on synthetic inputs. Moreover, millets leave behind substantial biomass, which can be used for animal feed or as organic matter to improve soil health.

**III. Nutritional Profile of Millets**

***A. Macronutrients***

Millets are valued for their rich macronutrient composition, which includes complex carbohydrates, moderate amounts of high-quality protein, and healthy fats. They serve as ideal alternatives to refined cereals due to their enhanced nutritional density and metabolic benefits. These grains play a critical role in managing metabolic disorders, supporting digestive health, and maintaining satiety.

***1. Carbohydrates – complex carbs and low glycemic index***

Millets are predominantly composed of carbohydrates, ranging from 60% to 75% by weight, depending on the species (Bhatt *et.al.,* 2022). Unlike refined grains, millets are rich in complex carbohydrates that break down slowly during digestion, contributing to a sustained release of glucose into the bloodstream. The presence of resistant starch and non-starch polysaccharides contributes to this property.

Glycemic index (GI) values for most millets are significantly lower than those of polished rice and white bread. For example, foxtail millet and little millet exhibit GI values between 50 and 54, compared to white rice, which typically scores above 70. This makes millets particularly beneficial for individuals managing type 2 diabetes and insulin resistance.

***2. Protein quality and content compared to cereals***

Millets contain moderate levels of protein, typically between 7% and 13%, depending on the variety (Saleh *et.al.,* 2013). Proso millet contains approximately 12.5% protein, while pearl millet has around 11.6%, and finger millet contains about 7.7%. Although their protein content may appear similar to that of wheat and maize, the quality of millet protein is superior in terms of digestibility and essential amino acid composition.

Most millet proteins are rich in methionine and cysteine, sulfur-containing amino acids that are deficient in many other cereals. Finger millet, for example, contains up to 5.4% essential amino acids and is especially rich in tryptophan, lysine, and threonine (Thagunna *et.al.,* 2022). This profile supports muscle synthesis, tissue repair, and metabolic regulation, making millets a valuable food for vegetarian and vegan diets.

***3. Fats – essential fatty acids and low-fat content***

Millets are generally low in fat, with total lipid content ranging between 1% and 5%. The fat profile is dominated by unsaturated fatty acids, particularly linoleic acid and oleic acid. Pearl millet contains about 5% fat, of which more than 70% is unsaturated fatty acids. These healthy fats contribute to cardiovascular protection and cellular integrity.

The presence of essential fatty acids in millets enhances their nutritive value without significantly increasing calorie density (Tripathi *et.al.,* 2021). Millets also have a natural advantage due to their lipid-stabilising properties, which contribute to a longer shelf life when stored properly.

***B. Micronutrients***

Millets are rich sources of essential vitamins and minerals that are critical for immune function, bone health, enzymatic reactions, and overall cellular metabolism. They provide a wide range of micronutrients often lacking in high-yielding cereal grains.

***1. Vitamins – B-complex vitamins, vitamin E***

Millets are excellent sources of B-complex vitamins, including niacin (B3), riboflavin (B2), thiamine (B1), pyridoxine (B6), and folic acid (B9), which play vital roles in energy metabolism, nervous system function, and red blood cell production. Finger millet, for instance, provides around 1.1 mg of niacin and 0.34 mg of riboflavin per 100 grams, which is higher than levels found in most common cereals (Henley *et.al.,* 2010).

Vitamin E, a potent antioxidant, is present in trace amounts across various millet species. While its concentration is generally lower than in oilseeds, it contributes to the oxidative stability and health-promoting properties of millet-based diets.

***2. Minerals – iron, calcium, magnesium, phosphorus, zinc***

Millets offer high concentrations of essential minerals. Finger millet is notable for its exceptional calcium content, averaging 344 mg per 100 grams—approximately ten times that of wheat and rice (Anitha *et.al.,* 2021). This makes it highly beneficial for bone development, especially in children and pregnant women. Pearl millet provides around 8 mg of iron per 100 grams, supporting the prevention of iron-deficiency anaemia.

Millets are also rich in magnesium (114 mg/100g in foxtail millet), phosphorus (285 mg/100g in proso millet), and zinc (2.3–4.2 mg/100g in various species), all of which contribute to cellular functions, enzyme activation, and immune system support.

***C. Dietary Fibre Content***

Millets are high in dietary fibre, both soluble and insoluble. The fibre content ranges from 7% to 18%, depending on the species and processing method. Finger millet contains the highest fibre content among commonly consumed millets, contributing significantly to satiety, improved bowel movement, and reduced cholesterol absorption (Devi *et.al.,* 2014).

The fibre in millets also plays a role in modulating the gut microbiota and slowing the absorption of sugars, which supports metabolic health and reduces the risk of lifestyle-related diseases such as obesity and type 2 diabetes.

***D. Phytochemicals and Antioxidants***

Millets are rich in bioactive compounds, including polyphenols, flavonoids, lignans, and phytosterols. These phytochemicals exhibit antioxidant, anti-inflammatory, antimicrobial, and anticancer properties. Finger millet has been reported to contain 0.3% to 3% polyphenols, primarily ferulic acid, gallic acid, and catechins (Xiang *et.al.,* 2019). These compounds neutralise free radicals, reduce oxidative stress, and contribute to the prevention of chronic diseases.

Foxtail millet and kodo millet have been shown to exhibit high radical-scavenging activity and lipid peroxidation inhibition, suggesting their potential in reducing oxidative damage and supporting cardiovascular health.

***E. Anti-nutritional Factors***

Although millets offer substantial nutritional advantages, they also contain certain anti-nutritional compounds that may interfere with nutrient absorption and bioavailability (Singh *et.al.,* 2025). The most common are phytates, tannins, and oxalates.

***1. Phytates, tannins, oxalates***

Phytates can bind to minerals such as iron, zinc, and calcium, forming insoluble complexes that reduce their bioavailability. Tannins, primarily found in the seed coat, may inhibit the activity of digestive enzymes like amylase and protease. Oxalates may also hinder calcium absorption and contribute to the formation of kidney stones when consumed in excess.

Despite these concerns, the levels of these compounds are often not high enough to pose health risks in individuals consuming diverse diets (Renwick *et.al.,* 2003). Moreover, several traditional and modern processing techniques can significantly reduce their concentration.

***2. Methods to reduce anti-nutritional compounds (e.g., fermentation, soaking)***

Soaking, germination, fermentation, roasting, and decortication are effective methods for reducing anti-nutritional factors in millets. Fermentation can reduce phytate content by up to 50%, while soaking and sprouting can enhance mineral bioavailability by activating endogenous phytase enzymes. Germination of finger millet has been shown to increase iron bioavailability and reduce tannin content, enhancing overall nutritional value.

**IV. Health Benefits of Millets**

***A. Glycemic Control and Diabetes Management***

Millets play a critical role in the dietary management of diabetes mellitus due to their complex carbohydrate profile, high dietary fibre content, and presence of bioactive compounds (Singh *et.al.,* 2022). These characteristics contribute to a slower digestion rate and improved postprandial glucose regulation, making millets a suitable component of therapeutic diets.

***1. Low glycemic index***

Millet grains exhibit a lower glycemic index (GI) compared to refined cereals such as white rice or white bread. Finger millet, foxtail millet, and little millet have GI values ranging from 50 to 54, while the GI of white rice exceeds 70. The low GI is primarily attributed to the higher content of slowly digestible starch, resistant starch, and soluble dietary fibre, which collectively contribute to delayed glucose absorption in the intestine.

Consuming low-GI foods is associated with reduced insulin spikes and improved glycemic control, particularly in individuals with type 2 diabetes and impaired glucose tolerance (Vlachos *et.al.,* 2020). Incorporation of millets into meals can help stabilise blood sugar levels over time.

***2. Studies on glucose regulation***

Controlled clinical studies have demonstrated that millet-based diets can significantly lower fasting blood glucose levels, postprandial glucose response, and glycated haemoglobin (HbA1c) in diabetic patients. A randomised dietary intervention showed that finger millet and kodo millet significantly reduced postprandial glucose and insulin response compared to polished rice. Another study reported a 26% reduction in fasting blood glucose after eight weeks of consuming a foxtail millet-based diet in adults with type 2 diabetes (Ren *et.al.,* 2018).

These outcomes support the inclusion of millets in low-GI meal planning for effective diabetes management and prevention of complications associated with long-term hyperglycemia.

***B. Cardiovascular Health***

The cardioprotective effects of millets are supported by their rich content of fibre, antioxidants, unsaturated fatty acids, and phytosterols. Regular consumption contributes to improved blood pressure regulation and cholesterol management, which are key factors in preventing cardiovascular disease.

***1. Blood pressure regulation***

Millets are naturally high in magnesium and potassium, minerals essential for regulating vascular tone and blood pressure (Ambati *et.al.,* 2019). Magnesium acts as a vasodilator and modulates calcium levels within vascular smooth muscle cells, reducing arterial stiffness. Potassium assists in counteracting the hypertensive effects of dietary sodium. Foxtail millet, with approximately 114 mg of magnesium per 100 grams, supports vascular function and reduces the risk of hypertension.

Animal model studies have also indicated that millet polyphenols may suppress angiotensin-converting enzyme (ACE) activity, a critical mechanism in controlling blood pressure.

***2. Cholesterol-lowering effects***

Millets contain soluble dietary fibres and phytosterols that bind bile acids and reduce the absorption of cholesterol in the intestine (Singh *et.al.,* 2019). This mechanism leads to decreased plasma levels of total cholesterol and LDL-cholesterol. A study revealed that a diet incorporating barnyard millet reduced LDL-cholesterol by 13% and total cholesterol by 9% in hyperlipidemic subjects over 12 weeks.

Polyphenolic compounds in millets, such as ferulic acid and catechins, contribute to the inhibition of lipid peroxidation, improving overall lipid profiles and reducing atherosclerotic risk.

***C. Gastrointestinal Health***

Millets promote gastrointestinal health through their high content of insoluble and soluble fibres, prebiotic properties, and non-gluten structure (Ajibade *et.al.,* 2020). These characteristics enhance digestion, support gut microbiota, and protect against various digestive disorders.

***1. Digestive benefits of dietary fibre***

Millets, particularly finger millet and little millet, provide 11–18% dietary fibre, significantly higher than wheat or polished rice. This fibre increases stool bulk, shortens intestinal transit time, and supports peristalsis, reducing the likelihood of constipation. Insoluble fibre passes through the gut intact, promoting mechanical cleansing of the colon and preventing the accumulation of toxins.

Soluble fibre, on the other hand, is fermented in the colon into short-chain fatty acids (SCFAs) that nourish the gut lining and modulate inflammation, contributing to colon health (Wong *et.al.,* 2006).

***2. Role in preventing constipation and IBS***

Regular intake of high-fibre millets has been associated with a reduction in symptoms of irritable bowel syndrome (IBS), including bloating, gas, and irregular bowel habits. Millet-based diets improve intestinal motility and help in regulating bowel frequency. Clinical evidence from interventions using finger millet flour has shown symptomatic relief in patients with functional constipation and mild IBS over a 6-week dietary period.

***D. Obesity and Weight Management***

Millets aid in weight control through mechanisms related to appetite regulation, low energy density, and metabolic enhancement (Kumar *et.al.,* 2025). Their nutritional profile supports satiety without contributing to excessive caloric intake.

***1. Satiety and appetite control***

Millets are rich in fibre and complex carbohydrates that digest slowly, increasing the feeling of fullness and delaying hunger signals. This satiety-promoting property leads to reduced overall food intake and helps in controlling body weight. A study found that individuals consuming millet porridge experienced a 21% lower calorie intake at the next meal compared to those consuming rice porridge, attributed to prolonged satiety.

The role of resistant starch in millets also extends gastric emptying time, reducing the frequency of meals and snacking behaviours associated with weight gain (Hayes *et.al.,* 2021).

***2. Metabolic advantages***

Millet-based diets improve insulin sensitivity, reduce lipid accumulation, and enhance fat oxidation. These metabolic advantages help reduce visceral fat and body mass index (BMI). Intervention studies involving overweight individuals showed significant improvements in metabolic markers, including reductions in waist circumference and serum triglycerides, after eight weeks of millet consumption.

Millets’ ability to modulate the gut microbiome may also contribute to better metabolic outcomes through improved nutrient absorption and hormonal signalling.

***E. Bone Health***

***1. Calcium and phosphorus in finger millet***

Finger millet is a superior source of calcium, offering approximately 344 mg per 100 grams, compared to 10 mg in white rice and 30 mg in wheat (Anitha *et.al.,* 2021). This high calcium concentration supports bone mineralisation, prevents osteoporosis, and is particularly beneficial for children, pregnant women, and the elderly. Phosphorus, present at around 283 mg per 100 grams, works synergistically with calcium to maintain bone density and strength.

Bioavailability of these minerals can be enhanced through processing techniques like fermentation and malting, which break down anti-nutritional factors and improve absorption.

***F. Antioxidant and Anti-inflammatory Properties***

Millets contain a wide range of antioxidant compounds including flavonoids, phenolic acids, and tannins, which play a key role in reducing oxidative stress and inflammation (Kaur *et.al.,* 2019). These antioxidants scavenge free radicals, prevent lipid peroxidation, and protect cellular structures from oxidative damage. Finger millet polyphenols have demonstrated potential in reducing biomarkers of inflammation, including TNF-α and interleukin-6, in animal models.

Chronic inflammation is a precursor to several degenerative diseases such as cancer, cardiovascular disorders, and diabetes. Regular consumption of antioxidant-rich foods like millets contributes to disease prevention and improved immune response.

***G. Gluten-free Nature and Suitability for Celiac Patients***

Millets are naturally gluten-free, making them safe for individuals with celiac disease and non-celiac gluten sensitivity (Asrani *et.al.,* 2023). Gluten, a protein complex found in wheat, barley, and rye, can trigger immune-mediated damage in the small intestine in susceptible individuals. Millets offer a nutritious and diverse alternative to gluten-containing cereals without compromising dietary variety or nutrient intake.

Multiple clinical studies confirm the absence of gluten in all commonly consumed millets, including foxtail, pearl, and finger millet. Millet-based flours and porridges have become important components of gluten-free dietary interventions, especially for children and patients requiring long-term gluten elimination.

**V. Processing and Preparation of Millets**

***A. Traditional preparation techniques***

Millets have been consumed for thousands of years through a variety of traditional culinary methods adapted to local conditions and cultural practices (Rai *et.al.,* 2008). Common techniques include soaking, boiling, steaming, roasting, and fermenting. Soaking and boiling soften the grains and reduce anti-nutritional compounds, making essential nutrients more bioavailable.

Fermented millet products are widely prepared and consumed in several parts of Asia and Africa. Traditional foods such as fermented porridge, gruel, and steamed cakes are made using natural or starter-based fermentation methods. These processes enhance the palatability, digestibility, and shelf life of millets. Finger millet is often fermented into a mildly acidic gruel known to promote gut health and support iron absorption. Similarly, steaming millet flour to make dumplings or pancakes preserves nutrients and creates soft-textured meals suitable for children and the elderly.

Roasting and puffing are also commonly practised to improve flavour, reduce moisture content, and increase storage stability (Swarnakar *et.al.,* 2022). These low-cost traditional processes contribute to the preservation and popularity of millet-based foods in rural and peri-urban regions.

***B. Modern processing methods***

Advancements in food processing technology have expanded the scope of millets in commercial food products. Mechanical and thermal methods now allow for the transformation of raw millet grains into a variety of shelf-stable, ready-to-use, and value-added forms.

***1. Milling, puffing, extrusion, fermentation***

Milling involves the removal of the outer fibrous husk, bran, and germ to produce refined flour or semolina (Kaushal *et.al.,* 2022). Although milling improves the texture and appearance of millets, it can lead to the loss of dietary fibre, minerals, and polyphenols concentrated in the outer layers. Decortication is often applied prior to milling to remove indigestible hulls while preserving the endosperm.

Puffing is a high-temperature, short-time (HTST) process that rapidly expands the grain, improving sensory attributes such as crispness and flavour (Katkar *et.al.,* 2024). This technique also improves starch digestibility and is commonly used to produce breakfast cereals and snack items. Studies show puffed millets retain significant levels of iron and dietary fibre when processed under optimised conditions.

Extrusion combines high temperature, pressure, and mechanical shear to convert millet flours into expanded products such as noodles, snack pellets, and cereal bars. It allows fortification with micronutrients and incorporation of bioactive compounds. Extruded millet products demonstrate good digestibility and shelf stability, and are increasingly used in school meal programs and nutraceuticals.

Controlled fermentation is another modern technique used to enhance flavour, increase nutrient bioavailability, and introduce probiotic benefits (Roobab *et.al.,* 2020). Fermentation of millet-based doughs with selected microbial strains can reduce phytic acid by up to 60% and increase the bioaccessibility of iron and zinc. Fermented millet beverages and porridges are gaining traction as functional foods in health-conscious consumer markets.

***C. Impact of processing on nutritional content***

Processing significantly alters the nutritional profile of millets, sometimes positively and sometimes adversely, depending on the method and intensity of processing. Milling tends to reduce the content of fibre, minerals (especially iron, zinc, and magnesium), and phytochemicals, which are mostly located in the outer seed layers.

Thermal treatments such as roasting and puffing can preserve antioxidants and improve the bioavailability of phenolic compounds, but may also degrade certain heat-sensitive vitamins like thiamine and folate (Emmanuel *et.al.,* 2025). High-temperature extrusion often reduces antinutritional factors while enhancing protein digestibility and starch gelatinisation, which aids nutrient absorption.

Fermentation and germination are particularly effective at improving nutritional quality. These biological processes increase the content of certain B vitamins, decrease phytates and tannins, and enhance enzymatic digestibility. For example, germinated finger millet flour has been reported to show significantly higher levels of bioavailable calcium and iron compared to its raw counterpart.

Optimal processing strategies aim to balance sensory appeal, shelf life, and nutrient preservation to maximise the value of millet-based foods for both traditional and modern consumers (Mishra *et.al.,* 2024).

***D. Development of millet-based functional foods***

As awareness of health-focused nutrition continues to grow, millets are increasingly incorporated into functional foods—products formulated not just for basic nutrition, but also for promoting health and preventing disease. The versatility of millets enables their inclusion in a wide range of modern food categories.

***1. Ready-to-eat products***

Millet-based ready-to-eat (RTE) products are expanding rapidly in both rural and urban markets. These include instant porridges, extruded breakfast cereals, puffed snacks, health bars, and fortified energy drinks. Finger millet, foxtail millet, and pearl millet are commonly used due to their favourable cooking properties and nutritional profiles (Sharma *et.al.,* 2018).

Consumer surveys have shown increasing preference for millet RTEs among health-conscious adults seeking high-fibre, low-GI, and gluten-free options. Products such as sprouted millet granola, instant upma mixes, and millet flake cereals offer convenience without compromising on nutrient density. Millet-based RTEs are also used in maternal and child nutrition programs due to their ease of preparation and digestibility.

***2. Bakery and snack items***

Millet flours are now being incorporated into bakery formulations to produce healthier alternatives to conventional products (Siddiqui *et.al.,* 2022). Biscuits, cookies, cakes, and breads made from finger millet and foxtail millet provide higher levels of dietary fibre, calcium, and polyphenols than wheat-based equivalents. Studies have shown that incorporating up to 40% millet flour into bakery items does not significantly alter sensory acceptability while improving nutritional content.

Snack foods made from extruded millet blends are increasingly marketed as low-fat, high-fibre options suitable for diabetic and obese populations. Millet noodles and pasta have also emerged as gluten-free replacements in specialised diets. These innovations in product development have helped reposition millets from “coarse grains” to “smart foods” in the modern food ecosystem.

**VI. Millets in Modern Diets and Food Systems**

***A. Consumer awareness and acceptance***

There has been a growing shift in dietary preferences toward more natural, whole-grain, and nutrient-dense foods, which has opened opportunities for the revival of millets (Yadav *et.al.,* 2024). Consumers are increasingly seeking alternatives to highly refined cereals, particularly those with lower glycemic indices and higher fibre content. Despite this interest, the actual level of awareness regarding millets, their nutritional value, and their culinary versatility remains limited across many urban and semi-urban populations.

Studies have shown that while over 70% of surveyed individuals recognise millets as “healthy,” only about 35% regularly include them in their meals. Reasons for lower adoption include a lack of familiarity with preparation methods, a perception of poor taste, and limited product availability in supermarkets. Marketing campaigns, social media education, and cooking demonstrations have been identified as effective tools to raise awareness and reshape perceptions surrounding millets (Singh *et.al.,* 2023).

Increased media attention, supported by food influencers, chefs, and nutritionists, is slowly helping rebrand millets from “coarse grains” to “smart foods.” The shift in public perception is key to encouraging regular consumption and driving demand.

***B. Integration into dietary guidelines and national nutrition programs***

Millets are increasingly being recognised in formal nutrition policies and dietary guidelines across various regions (Rawat *et.al.,* 2023). Their inclusion is supported by scientific evidence demonstrating their role in addressing micronutrient deficiencies, metabolic disorders, and undernutrition.

National nutrition programs have begun incorporating millet-based formulations in school feeding schemes, maternal nutrition support, and public distribution systems. The Food and Agriculture Organisation has promoted millets as part of sustainable diets, aligning with the UN Sustainable Development Goals (SDGs), particularly those targeting hunger (SDG 2), health (SDG 3), and sustainable agriculture.

Dietary guidelines published by global health organisations now emphasise the consumption of whole grains, including sorghum and millets, as part of a balanced diet (Seal *et.al.,* 2016). Such policy-level support strengthens millet’s positioning as a critical component of nutrition-sensitive agriculture.

***C. Role in food security and nutrition in developing countries***

Millets offer significant potential for enhancing food security and nutritional outcomes in regions vulnerable to climatic stress and economic instability. Their resilience to drought, ability to thrive in low-fertility soils, and short growing seasons make them ideal for farming communities operating in marginal agro-ecological zones.

The high nutrient density of millets contributes to combating hidden hunger—micronutrient deficiencies that are widespread among low-income populations (Srivastava *et.al.,* 2021). For example, finger millet's high calcium and iron content can address bone health and anaemia, while the overall fibre and protein profile of millets supports general dietary adequacy in staple-based diets.

Millets also support women-led agriculture and smallholder farmers due to their low input costs and compatibility with mixed-cropping systems. This makes them an important tool in promoting rural livelihoods and inclusive agricultural growth.

***D. Economic and market perspectives***

The reintroduction of millets into mainstream markets is gradually transforming them from subsistence crops to commercial commodities. Their increasing demand in health food segments, urban grocery chains, and export markets has sparked renewed interest from agribusinesses and policymakers.

***1. Trends in millet production and consumption***

Global production of millets reached approximately 30 million metric tonnes in 2021, with Africa contributing over 55% and Asia about 35% (Deevi *et.al.,* 2024). Despite this, millets account for less than 3% of total global cereal consumption. There has been a slight decline in millet cultivation area in recent decades due to shifts toward high-yielding cereals, but this trend is now showing signs of reversal.

Rising consumer demand for gluten-free and low-GI grains has contributed to the increased millet processing and packaging industries. Millet-based flours, snacks, breakfast cereals, and health drinks are now widely available in urban and international markets, particularly in Asia, Europe, and North America. Companies are beginning to invest in product innovation, branding, and retail visibility for millet products.

***2. Challenges in commercialisation, and marketing***

Despite positive market signals, several challenges hinder the large-scale commercialisation of millets (Patil *et.al.,* 2023). The supply chain remains underdeveloped, particularly in terms of post-harvest infrastructure, storage, and logistics. Millets are often grown in rain-fed, dispersed farming systems that limit consistent supply and quality control.

Marketing efforts have also struggled with consumer perceptions linking millets to poverty or rural diets. Product standardisation, attractive packaging, and pricing strategies are needed to expand consumer bases beyond niche health markets. The lack of processing equipment suited specifically to millet grains adds another barrier, making large-scale value addition more difficult than with wheat or rice.

Capacity-building initiatives, farmer cooperatives, and public-private partnerships have been suggested as key enablers to scale up millet markets (Thorpe *et.al.,* 2015). Government procurement policies and subsidies can also encourage wider cultivation and consumption.

**VII. Challenges and Limitations**

***A. Presence of anti-nutritional factors***

Millets contain anti-nutritional compounds such as phytates, tannins, and oxalates, which interfere with the absorption of key micronutrients like iron, zinc, and calcium. These compounds can reduce bioavailability by forming insoluble complexes, particularly in raw or minimally processed forms. Although methods like fermentation, germination, and roasting can mitigate their effects, many consumers and small-scale producers lack access to appropriate processing knowledge or technologies (Ogunlade *et.al.,* 2025).

***B. Taste and texture preferences of consumers***

Many consumers express dissatisfaction with the coarse texture, bland flavour, or earthy aftertaste of certain millet varieties. These sensory characteristics reduce the appeal of millets when compared to polished cereals like rice and wheat. Limited familiarity with millet-based recipes and the absence of standardised processing methods have also restricted their adoption in mainstream diets.

***C. Lack of widespread awareness and education***

Awareness of the nutritional and ecological value of millets remains low among both consumers and health professionals (Rizwana *et.al.,* 2023). Surveys have shown that although many recognise millets as traditional foods, few associate them with modern health benefits or know how to incorporate them into daily meals. The absence of targeted educational campaigns has hindered millet's visibility in public health discourse.

***D. Supply chain and policy-related issues***

Weak supply chains, inadequate post-harvest infrastructure, and the lack of value chain integration pose serious barriers to millet commercialisation. Fragmented production systems limit the availability of uniform quality grain for processing. Moreover, existing agricultural policies and market incentives often favour major cereals, leading to underinvestment in millet research, procurement, and support services.

**VIII. Future Prospects and Research Directions**

***A. Breeding and genetic improvement of millet varieties***

Advanced breeding techniques are being employed to develop high-yielding, disease-resistant, and climate-resilient millet cultivars (Nagaraja *et.al.,* 2024). Molecular tools, such as marker-assisted selection and genome editing, are helping identify and enhance traits linked to nutrient density, grain size, and drought tolerance. Improved varieties can increase productivity and make millet cultivation more economically attractive.

***B. Biofortification and nutrient enhancement***

Biofortification efforts are underway to enhance the micronutrient content of millets through conventional breeding and agronomic practices. Focus areas include increasing iron, zinc, calcium, and amino acid levels to address hidden hunger. Pearl millet lines with iron concentrations above 80 mg/kg have already shown promise in reducing anaemia risks.

***C. Role of millets in personalised nutrition***

Emerging fields such as nutrigenomics and personalised nutrition are exploring the compatibility of millets with individual metabolic profiles (Susmitha *et.al.,* 2024). Their low glycemic index, gluten-free nature, and diverse phytochemical content make them suitable candidates for customised diets aimed at managing obesity, diabetes, and cardiovascular conditions. More research is required to map specific millet components to genetic and lifestyle variables.

***D. Further clinical studies on health effects***

Although preliminary data support the health benefits of millets, larger, long-term clinical trials are essential to substantiate their effects on chronic diseases. Future studies should explore biomarkers of inflammation, cardiovascular risk factors, gut microbiota modulation, and cognitive health outcomes associated with millet-based diets.

***E. Potential for millets in combating climate change and malnutrition***

Millets contribute to sustainable food systems due to their minimal water requirement, tolerance to heat, and ability to grow in degraded soils. Their inclusion in crop diversification strategies helps reduce environmental stress and enhances food security. By simultaneously addressing nutrient gaps and supporting ecological balance, millets offer a dual solution to the twin challenges of malnutrition and climate change (Vidhya *et.al.,* 2023).

**IX. Conclusion**
Millets represent a nutritionally rich and environmentally sustainable class of cereals with immense potential to address global health and food security challenges. Their high content of fibre, essential amino acids, vitamins, minerals, and bioactive compounds supports the prevention and management of non-communicable diseases such as diabetes, cardiovascular disorders, and obesity. As gluten-free grains with low glycemic indices, millets are well-suited for specialised dietary needs. Their resilience to climate stress and low input requirements further positions them as critical crops for sustainable agriculture. Despite their benefits, widespread adoption remains limited due to consumer preferences, anti-nutritional factors, and market constraints. Targeted efforts in processing, public education, and policy integration are essential to enhance their acceptance. Continued research on biofortification, clinical efficacy, and food innovations will play a key role in establishing millets as mainstream components of modern diets and functional foods.

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