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Millets as Sustainable Functional Foods: Nutritional Value, Therapeutic Potential, and Processing Perspectives

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Abstract
Millets gaining global recognition as functional foods due to their rich nutritional composition, bioactive compounds, and therapeutic potential. They are climate-resilient and underutilized cereals, millets such as finger millet, pearl millet, foxtail millet, and sorghum are rich sources of dietary fiber, high-quality proteins, essential minerals (iron, calcium, zinc), vitamins, and bioactive compounds including phenolics, flavonoids, and antioxidants. Regular consumption of millets has been associated with multiple health benefits, including improved glycemic control, reduced risk of cardiovascular diseases, enhanced gut health, and potential protection against obesity and certain metabolic disorders. Beyond their nutritional advantages, millets exhibit significant functional properties that make them suitable for the development of value-added food products. However, the presence of antinutritional factors such as phytates and tannins can affect nutrient bioavailability. Traditional and modern processing techniques including soaking, germination, fermentation, roasting, extrusion, and milling—play a crucial role in enhancing nutrient availability, reducing antinutrients, and improving sensory and techno-functional properties. This review consolidates current knowledge on the nutritional profile, therapeutic benefits, and processing-induced changes in millets, highlighting their role as sustainable and health-promoting foods for modern diets. The findings emphasize the potential of millets in functional food development and their contribution to global food and nutritional security.

Keywords: Nutritional Composition, Bioactive Components, Therapeutic Benefits, Antinutritional Factors, Sustainable Foods

Introduction

Millets are a category of small-seeded cereal grains that have garnered increasing recognition as functional foods, owing to their rich nutritional profile, health-promoting attributes, and resilience to challenging agro-climatic conditions. Traditionally consumed in Asia and Africa, millets are now being acknowledged worldwide as sustainable alternatives to primary cereals like rice, wheat, and maize. Their inherent gluten-free characteristic, low glycemic index, and high levels of dietary fiber, minerals, and bioactive compounds render them particularly beneficial for managing lifestyle-related disorders such as celiac disease, type 2 diabetes mellitus, and cardiovascular diseases. From a nutritional standpoint, millets are regarded as nutrient-dense grains, offering substantial amounts of protein, complex carbohydrates, essential amino acids, and micronutrients including iron, calcium, magnesium, and B-complex vitamins. Millets also help hydrate the colon, preventing constipation. Niacin found in millet can assist in lowering cholesterol levels. Furthermore, they encompass a diverse array of phytochemicals, such as polyphenols and antioxidants, which enhance their functional and therapeutic potential by demonstrating anti-inflammatory, antioxidant, and glycaemic-regulating properties. These attributes position millets as promising candidates for incorporation into contemporary health-oriented and functional food formulations. Despite their nutritional and therapeutic benefits, the use of millets in mainstream food systems remains restricted, particularly in developed areas, due to challenges related to taste, texture, and the presence of anti-nutritional factors like phytates, tannins, and phenolic compounds. These elements can diminish mineral bioavailability and lead to undesirable sensory traits such as bitterness and astringency. As a result, processing interventions are crucial in enhancing both the nutritional quality and consumer acceptability of millet-based products. Processing methods such as germination, decortication, fermentation, and others are essential for improving the overall quality of millets and their derivatives.

Classification of Millets

Millets are categorized into major and minor groups primarily based on the size of the grains, the scale of production, and the extent of cultivation. The major millets consist of sorghum, pearl millet, and finger millet, whereas the minor millets include proso millet, barnyard millet, and foxtail millet. [1]

Major Millets

Millets classified as major are typically larger-grained cereals that play a significant role in both cultivation and dietary practices. They belong to the Poaceae (grass) family and are widely consumed throughout India:

- Sorghum (*Sorghum bicolor*)—also referred to as Jowar
- Pearl Millet (*Pennisetum glaucum*)—commonly known as Bajra
- Finger Millet (*Eleusine coracana*)—often called Ragi/Mandua

These millets form the primary group due to their extensive cultivation area and nutritional significance [2].

Minor Millets

Minor millets are characterized by their smaller seeds and are also part of the Poaceae family. They have been traditionally cultivated and consumed in various regions, albeit with a comparatively smaller production share:

- Foxtail Millet (*Setaria italica*)—known as Thinai/Kangni/Kakun
- Proso Millet (*Panicum miliaceum*)—referred to as Cheena/Barri
- Kodo Millet (*Paspalum scrobiculatum*)—called Kodo
- Barnyard Millet (*Echinochloa frumentacea / Echinochloa crus-galli*)—known as Sanwa/Sawa/Jhangora

This category is recognized as the "small millets," which are appreciated for their drought resistance, nutritional advantages, and incorporation into traditional diets [3].

Nutritional Profile of Millets

Millet crops have long been recognized for their significant contribution to a nutritious diet. It is well-documented that millet-based diets provide a rich supply of phytoconstituents, vitamins, minerals, and fibrous materials, known as non-starch polysaccharides, which are vital for normal growth, the management of type 2 diabetes, and overall nutritional well-being [4]. Additionally, foods derived from millet are considered potential prebiotics and probiotics, offering substantial health benefits [5]. Millets high in phenolics are of particular importance to health, aging, and metabolic syndrome [6].

Table 1 Nutritional Composition of Millets

Millets varieties	Carbo hydrate (g)	Protein (g)	Fat (g)	Energy (kcal)	Crude fibre (g)	Calcium (mg)	Iron (mg)
Majormillets							
Finger millet	72.0	7.3	1.3	3-08	3.6	344	3.9
Pearl millet	67.5	1.6	5.0	361	1.2	42	8.0
Sorghum	72.6	10.4	1.9	349	1.6	25	4.1
Minormillets							
Porso millet	70.4	12.5	1.1	341	2.2	14	0.8
Barny ard	65.5	6.2	2.2	307	9.8	20	5.0
Foxtail millet	60.9	12.3	4.3	331	8.0	31	2.8

Source: Nutritional value of Indian foods, NIN, 2007.

Table 2 Vitamin Profile of Minor and Major Millets

Millets varieties	Thiamine (mg)	Niacin (mg)	VitA (mg)	Folic Acid (mg)	Vitb5 (mg)	VitE (mg)
Majormillets						
Finger millet	0.42	1.1	42	18.3	-	22.0
Pearl millet	0.38	2.8	132	45.5	1.09	19.0
Sorghum	0.38	4.3	47	20.0	1.25	12.0
Minormillets						
Porso millet	0.41	4.5	0	-	1.2	-
Barny ard	0.33	4.2	0	-	-	-
Foxtail millet	0.42	1.1	42	18.3	-	22.0

Source: Nutritional value of Indian foods, NIN, 2007.

Nutritional Profile of Each Millet

Finger Millet

Finger millet is recognized as one of the most nutritious cereals available, highly regarded for its natural calcium content which supports bone strengthening and reduces the risk of fractures. Additionally, it serves as a valuable source of natural iron, aiding in the prevention of anemia. Often considered a suitable substitute for rice or wheat, finger millet is a nutrient-dense food rich in proteins, amino acids, minerals, and vitamins. Its high fiber content makes it an effective laxative that aids in preventing constipation. Furthermore, due to its substantial calcium levels, finger millet is highly beneficial for infants, the elderly, pregnant women, and lactating mothers, as it enhances breast milk production. [7]

Finger millet is beneficial for various health conditions, including blood pressure, heart issues, and asthma. It is particularly advantageous for individuals with diabetes due to its role in promoting slow digestion and the gradual release of glucose into the bloodstream. Additionally, finger millet aids in increasing hemoglobin levels and combating malnutrition and degenerative diseases [8].

Pearl Millet

Pearl millet consists of magnesium which helps in reducing the respiratory problems in asthma patients and helps to reduce the effect of migraine. The fibre content of pearl millet helps the reduction of gall stone occurrence. The insoluble fibre present in pearl millet help in reduction of excessive bile in our system, as excessive bile in our system leads to gall stones [9].

Sorghum

Sorghum, an ancient cereal grain, serves as a staple food in India and Africa. It is regarded as a safe alternative for individuals with celiac disease or gluten sensitivity. Molecular evidence confirms that sorghum is entirely gluten-free, providing health benefits that make it a valuable addition to any diet. Gluten, a protein commonly found in grains such as wheat, barley, and rye, imparts a chewy, springy texture to baked goods like bread and pasta. Sorghum is thus utilized as a wheat substitute in products such as bread and pasta [7].

Research indicates that sorghum, also known as jowar, contributes to weight loss. Unlike major cereals such as rice and wheat, jowar offers a higher calcium content and is rich in iron, protein, and fiber. Studies have revealed that sorghum wax is abundant in policosanols, compounds known for lowering cholesterol levels. As a gluten-free grain, it is particularly favored by individuals with wheat intolerance [8].

Proso Millet

Proso millet is advantageous in preventing pellagra, a condition resulting from a deficiency of niacin (Vitamin B3), due to its high niacin content. Pellagra is a dermatological disease that leads to the skin becoming dry, scaly, and rough. Proso millet contains both protein and niacin, making it traditionally used as recuperative nourishment, particularly following pregnancy or illness [10].

Foxtail Millet

Foxtail millet contributes to the gradual release of glucose without disrupting the body's metabolism. Consuming foxtail millet is associated with a decreased prevalence of diabetes and is recognized for promoting heart health due to its rich magnesium content [8].

Bioactive Compounds of Millets

Millets are abundant in various bioactive compounds that enhance their health-promoting qualities and functional food attributes. Notable among these compounds are polyphenols, dietary fiber, phytosterols, antioxidants, and bioactive peptides, all of which play a crucial role in mitigating the risk of chronic diseases, including diabetes, cardiovascular disorders, and cancer [11].

Polyphenols

Millets are rich in phenolic acids and flavonoids, particularly within the seed coat. Notable phenolic acids include ferulic acid, p-coumaric acid, and caffeic acid, while flavonoids such as catechin and quercetin are known for their antioxidant and anti-inflammatory properties. These bioactive compounds play a crucial role in alleviating oxidative stress and enhancing metabolic health [12].

Dietary Fiber

Millets are superb sources of both soluble and insoluble dietary fiber, such as β-glucans, arabinoxylans, and resistant starch. These fibers contribute to the regulation of blood glucose levels, the enhancement of gut health, and the reduction of cholesterol absorption, ultimately lowering the risk of cardiovascular disease [13].

Antioxidants

The antioxidant potential of millets is attributed mainly to their phenolic content, tannins, and tocopherols. These antioxidants neutralize free radicals and protect cells from oxidative damage, supporting immune function and delaying aging-related disorders [14].

Phytosterols

Phytosterols such as campesterol, stigmasterol, and β-sitosterol are present in millet grains. These compounds help in reducing serum cholesterol levels by inhibiting cholesterol absorption in the intestine, thus promoting heart health [15].

Bioactive Peptides

During digestion or food processing, proteins in millets release bioactive peptides that exhibit antihypertensive, antioxidant, and antimicrobial characteristics. These peptides can inhibit the angiotensin-converting enzyme (ACE), thereby assisting in the regulation of blood pressure [16].

Tannins and Phytates

Millets contain antinutritional bioactive compounds such as tannins and phytic acid. While they can reduce mineral bioavailability, they also exhibit antioxidant and anticancer properties when consumed in moderate amounts [17].

Functional Properties of Millets

Finger millet (*Eleusine coracana*) demonstrates outstanding functional properties, including high water absorption and swelling power, making it highly suitable for bakery and weaning food formulations. Its abundant polyphenol and flavonoid content significantly enhances antioxidant activity and nutritional quality. Additionally, its moderate emulsifying and foaming capacities make it a viable component for use in composite flours [12].

Foxtail and proso millets are distinguished by their excellent pasting, gelation, and emulsification properties, rendering them ideal for applications in extrusion, noodles, and beverage formulations. Their high dietary fiber and phenolic content enhance their capability to induce a low glycemic response and provide significant antioxidant potential, thereby promoting their use in functional foods and those suitable for individuals with diabetes [18][19].

Barnyard millet exhibits significant water absorption capacity, swelling power, and binding properties, which contribute to improved texture and volume in baked goods and snacks. Additionally, its low glycemic index and high fiber content make it valuable in creating health-focused formulations [20].

Sorghum and pearl millet are distinguished by their robust starch gelatinization, as well as high oil and water absorption capacities, coupled with notable antioxidant activity. These attributes make them suitable for use in gluten-free, fermented, and thermally processed foods, while also offering health benefits linked to mineral bioavailability and gut health [20][21].

Table 4 Functional Properties of Millets

MilletType	Major Bioactive Compounds	Examplesof Compounds	Health/Functional Properties	Refe
Fingermillet (Eleusine coracana)	Polyphenols, dietaryfiber, phytates, tannins, antioxidants	Ferulicacid,catechin, quercetin, phytic acid	Strong antioxidant activity, anti-diabetic effect, improved guthealth, mineral chelation and cancer- preventive potential	[12]
Pearlmillet (Pennisetum glaucum)	Phenolic acids, flavonoids, phytosterols, dietary fiber	p-Coumaric acid, apigenin, β-sitosterol	Cholesterol- lowering, glycemic control, antioxidant and cardio protective effects	[13]
Sorghum (Sorghum bicolor)	Tannins, anthocyanins, phenolic acids, resistant starch	3-deoxyantho cyanidins, ferulicacid, condensed tannins	Anti-inflammatory, anticancer, antioxidant, improved gut health	[14]
Prosomillet (Panicum miliaceum)	Polyphenols, flavonoids, dietaryfiber, bioactive peptides	Quercetin, kaempferol, arabinoxylans	Antioxidantactivity, blood glucose regulation, antihypertensive potential	[15]
Barnyard millet (Echinochloa frumentacea)	Phenolic compounds, dietaryfiber, phytosterols	Caffeic acid, β- sitosterol, resistant starch	Low glycemic response, hypocholesterolemic effect, antioxidant activity	[16]
Foxtailmillet (Setaria italica)	Flavonoids, phenolic acids, bioactive peptides, antioxidants	Luteolin, ferulic acid, ACE-inhibitory peptides	Anti-diabetic, antihypertensive, antioxidant and metabolic health support	[17]

Therapeutic and Health Benefits of Millets

Millets possess considerable therapeutic potential attributed to their nutrient density, low glycemic index, and a wide range of bioactive compounds. Consistent consumption of millets has been closely linked to improved glycemic control, thus proving advantageous in diabetes management. Notably, the polyphenols found in finger millet and pearl millet play a role in inhibiting essential carbohydrate-digesting enzymes, such as α-amylase and α-glucosidase, consequently mitigating postprandial blood glucose spikes [22]. Furthermore, experimental studies have revealed that diets based on finger millet enhance antioxidant status and promote wound healing in diabetic models.

Millets play a significant role in promoting cardiovascular health due to their high levels of dietary fiber, magnesium, and phytosterols. These elements are instrumental in reducing serum cholesterol levels, managing blood pressure, and lessening oxidative stress, thereby collectively lowering the risk of cardiovascular diseases [23]. Furthermore, the phenolic compounds found in millets demonstrate anti-inflammatory and free-radical-scavenging properties, which are essential in the prevention of chronic metabolic disorders.

Therapeutic and Health Benefits of Millets: Evidence from Recent Studies

Recent scientific investigations have provided strong experimental and clinical evidence supporting the therapeutic efficacy of millets. A 2024 narrative review by [22] reported that regular consumption of finger millet–based diets significantly reduced fasting blood glucose and oxidative stress markers in diabetic animal models, primarily due to high polyphenol and dietary fiber content. These bioactive compounds inhibit α-amylase and α-glucosidase enzymes, thereby slowing carbohydrate digestion and glucose absorption. Pearl millet supplementation has been demonstrated to reduce plasma triglycerides and LDL cholesterol levels in hyperlipidemic rats, while also enhancing antioxidant enzyme activity [23]. The study attributes these benefits to the presence of phytosterols and magnesium, which are pivotal in enhancing lipid metabolism and regulating blood pressure.

A study conducted by [23] focused on processing techniques and revealed that fermented and germinated millets significantly improve mineral bioavailability, particularly for iron and zinc. These improvements subsequently enhanced hemoglobin levels in simulated dietary models. This research is especially pertinent for mitigating iron-deficiency anemia among populations at risk.

Furthermore, a recent review in Nutrition [24] highlighted that millet-rich diets promote gut microbial diversity and short-chain fatty acid production, improving gut integrity and reducing inflammation. The authors emphasized foxtail and barnyard millets as particularly effective for digestive wellness. Collectively, these studies affirm that millets serve not only as staple grains but also as therapeutic foods, backed by evidence demonstrating their benefits in metabolic regulation, cardiovascular protection, gut health, and management of micronutrient deficiencies.

Antinutritional Factors in Millets

Millets, a diverse group of small-seeded cereal grains, are extensively cultivated in semi-arid regions due to their resilience in harsh climatic conditions and minimal input requirements. Noted for their significant nutritional value, they are abundant in dietary fiber, essential minerals, vitamins, and bioactive compounds. In recent years, millets have garnered attention as sustainable functional foods, potentially enhancing food and nutritional security. However, their nutritional advantages are challenged by the presence of antinutritional factors, which impede nutrient bioavailability and affect digestibility, particularly in communities heavily dependent on cereal-based diets.

Antinutritional factors are naturally occurring compounds that interfere with the digestion, absorption, or utilization of nutrients. In millets, these compounds are predominantly located in the outer layers of the grain, such as the bran and seed coat. While these compounds may offer certain health benefits at low concentrations, their excessive presence can negatively impact mineral absorption and protein utilization [25].

Phytates (Phytic Acid)

Phytic acid serves as the main storage form of phosphorus in millets and is recognized as a major antinutritional factor that impacts the bioavailability of minerals. By forming insoluble complexes with divalent minerals like iron, zinc, calcium, and magnesium, it decreases their absorption within the human intestine. Diets rich in phytic acid are linked to mineral deficiencies, particularly in areas where millets and other cereals constitute dietary staples [26].

Tannins

Tannins are polyphenolic compounds commonly found in pigmented millet varieties, particularly sorghum and finger millet. They reduce protein digestibility by forming complexes with proteins and digestive enzymes. Additionally, tannins inhibit iron absorption, further contributing to micronutrient deficiencies when millet-based foods are consumed without adequate processing. [27]

Oxalates

Oxalates are organic acids capable of binding calcium to form insoluble calcium oxalate complexes, which limit calcium bioavailability. Finger millet has been reported to contain relatively high levels of oxalates compared to other cereals. Excessive intake of oxalates may contribute to reduced calcium absorption and increased risk of kidney stone formation.

Enzyme Inhibitors

Millets possess protease and amylase inhibitors that disrupt the activity of digestive enzymes, subsequently decreasing the digestibility of protein and starch. These inhibitors are regarded as heat-labile and can be substantially diminished through thermal processing techniques like cooking and roasting.

Processing Techniques of Millets

Millets, recognized for their high nutritional quality, climate resilience, and health benefits, are small-seeded cereals. Despite these advantages, they contain antinutritional factors like phytates, tannins, and polyphenols, which can hinder mineral bioavailability and protein digestibility. To address these issues, processing methods such as soaking, germination, fermentation, decortication, and thermal treatments are employed. These techniques enhance millets' nutritional, functional, and sensory properties while also improving their shelf life and consumer acceptance [28].

Finger Millet (*Eleusine coracana*)

The process of soaking and germination significantly increases the bioavailability of calcium and iron in finger millet grains while enhancing protein digestibility by reducing phytate and tannin levels. This germination process also boosts enzymatic activity, promoting the synthesis of bioactive compounds and improving starch digestion, as noted by [29]. Malting, which involves controlled germination followed by drying, amplifies amylase activity, rendering finger millet ideal for use in infant foods and malted beverages by improving flavor, lowering viscosity, and enhancing mineral absorption. Furthermore, the traditional fermentation of finger millet flour, as seen in foods like dosa and ambali, elevates B-vitamin content and optimizes protein quality through the microbial synthesis of essential amino acids. [30]

Proso Millet (*Panicum miliaceum*)

Dehulling/Decortication: The process of dehulling proso millet grains involves removing the fibrous husk to enhance palatability and cooking quality. It is important to note that excessive decortication can result in the depletion of essential dietary fibers and phenolic compounds [31].

Soaking and thermal processing, such as cooking or steaming, effectively reduce antinutritional factors and enhance starch gelatinization and digestibility. This process makes proso millet an ideal ingredient for porridge and extruded snacks, as documented by [32].

Extrusion cooking, characterized by high-temperature and short-duration processing, enhances the texture and shelf stability of ready-to-eat products, while also improving protein digestibility [33].

Foxtail Millet (*Setaria italica*)

Germination of foxtail millet results in increased levels of free amino acids, phenolic compounds, and antioxidant activity, while also enhancing sensory quality and mineral absorption, as noted by [34]. Lactic acid fermentation, according to [35], improves starch digestibility and decreases phytate content, rendering it ideal for use in fermented beverages and batters. Furthermore, dry roasting is effective in flavor enhancement, moisture content reduction, and extending shelf life by lowering microbial presence, as outlined by [36].

Barnyard Millet (*Echinochloa frumentacea*)

Dehulling, the process of removing the outer husk, improves cooking quality and decreases fiber-associated antinutrients, thereby enhancing mineral bioavailability [37]. Meanwhile, soaking before cooking can significantly reduce cooking time and enhance textural quality by ensuring uniform starch gelatinization. Puffing and roasting, as thermal techniques, improve digestibility and are frequently employed in producing ready-to-eat snack products with enhanced sensory characteristics [36].

Pearl Millet (*Pennisetum glaucum*)

Fermentation, utilizing both natural and starter cultures, enhances the bioavailability of iron and zinc while improving protein quality, and it imparts a distinctive sour flavor to traditional foods like injera and ogi [38]. Malting facilitates the enzymatic breakdown of starch and enhances mineral bioavailability, making pearl millet an ideal choice for malt-based beverages and infant weaning foods [37]. Heat treatment techniques such as roasting and steaming extend shelf life by deactivating lipase enzymes that initiate rancidity in pearl millet flour [39].

Sorghum (*Sorghum bicolor*)

The process of decortication involves the partial removal of bran, which leads to a decrease in tannin and phytate levels, thereby enhancing the digestibility of proteins and the bioavailability of minerals. Nonetheless, this may result in a reduction of dietary fiber and antioxidants [40]. Fermentation of sorghum is known to improve its amino acid profile while decreasing antinutritional compounds, making it a common practice in the production of traditional foods like kisra and injera [41]. Additionally, extrusion and baking techniques enhance texture, starch digestibility, and product variety, thus facilitating the creation of gluten-free bakery and snack items [42].

Processing methods, including soaking, germination, fermentation, malting, decortication, and thermal treatments, play a crucial role in enhancing the nutritional quality, functional properties, and sensory characteristics of millets. These techniques effectively decrease antinutritional factors, increase mineral bioavailability, and facilitate the creation of value-added millet-based products. By optimizing both traditional and modern processing technologies, there is potential for increased acceptance and usage of millets in functional and therapeutic foods.

Sustainability and Agricultural Importance of Millets

Millets are climate-resilient cereal crops that significantly contribute to food and nutritional security, especially in arid and semi-arid regions. Their minimal input requirements, resilience to drought and poor soils, and short growing cycles render them well-suited for sustainable agricultural systems in the face of changing climatic conditions. Millets promote biodiversity, enhance soil health, and support rural livelihoods, offering nutrient-rich grains that are abundant in dietary fiber, minerals, and bioactive compounds [43].

Finger Millet (*Eleusine coracana*)

Sustainability Aspects: Finger millet exhibits exceptional drought tolerance and can thrive in marginal soils with minimal fertilizer input. Its deep root system enhances soil structure and prevents erosion, making it suitable for rainfed farming systems. The crop also has a high capacity for carbon sequestration, contributing to climate change mitigation [44].

Agricultural Importance: Finger millet is a major source of calcium and iron, supporting nutritional security in resource-poor communities. Its long storage life reduces post-harvest losses, and its adaptability to intercropping systems enhances farm resilience and income stability [45].

Proso Millet (*Panicum miliaceum*)

Proso millet is recognized for its sustainability, being one of the most water-efficient cereal crops. It requires substantially less irrigation compared to rice or wheat. Its relatively short growing period of 60 to 90 days facilitates multiple cropping cycles and optimal land utilization, thereby alleviating pressure on natural resources [45]. In terms of agricultural significance, proso millet is integral to crop rotation systems as it disrupts pest and disease cycles. Furthermore, it offers diversified income opportunities for smallholder farmers, owing to its rising demand in health food markets and the livestock feed industry [46].

Foxtail Millet (*Setaria italica*)

Foxtail millet is characterized by its remarkable adaptability to drought-prone and low-fertility soils, showcasing an efficient nitrogen uptake that reduces reliance on synthetic fertilizers, thereby minimizing environmental pollution and production costs [46]. Agriculturally, it holds significant value in traditional farming systems and contributes to agro-biodiversity conservation. This millet is frequently employed in intercropping and mixed cropping practices, which enhance productivity and bolster resilience against climate variability [47].

Barnyard Millet (*Echinochloa frumentacea*)

Barnyard millet demonstrates significant sustainability attributes, notably its high tolerance to water stress, making it adaptable to both upland and lowland ecosystems. The millet's rapid growth and extensive canopy effectively suppress weed proliferation, thereby diminishing the need for chemical herbicides and fostering environmentally-friendly agricultural practices [48]. Agriculturally, barnyard millet plays a crucial role in ensuring food security, especially in tribal and hilly regions, due to its resilience under challenging conditions. Its compatibility with organic farming systems and appeal in niche markets provide economic advantages for small-scale farmers [49].

Pearl Millet (*Pennisetum glaucum*)

Sustainability Aspects: Pearl millet is one of the most drought- and heat-tolerant cereal crops, capable of producing grain under extreme temperatures and low rainfall. Its high biomass production contributes to soil organic matter and supports sustainable livestock integration [50].

Agricultural Importance: Pearl millet is a staple food in arid regions of Africa and South Asia, providing both grain and fodder. Its hybrid varieties have significantly improved yields, enhancing farmer incomes and regional food security [51].

Sorghum (*Sorghum bicolor*)

Sorghum is renowned for its exceptional drought resistance, attributed to its deep root system and waxy leaf surface, which contribute to efficient water usage. Commonly rotated with legumes, sorghum plays a pivotal role in enhancing soil nitrogen levels and supporting sustainable land management practices, as noted by Taylor and Emmambux in 2008. Its agricultural significance is further underscored by its versatility, being utilized for food, animal feed, fodder, and bioethanol production. Moreover, the crop's adaptability to a wide range of agro-climatic conditions positions it as a crucial element in climate-smart agriculture and a driver of rural economic development, as highlighted by Renzetti and Arendt in 2009.

Millets play a critical role in promoting sustainable agriculture and enhancing food system resilience. Their ability to thrive under low-input conditions, conserve water, improve soil health, and support agro-biodiversity makes them ideal crops for addressing the challenges of climate change and resource scarcity. By integrating millets into modern farming systems and value chains, policymakers and stakeholders can strengthen rural livelihoods, improve nutritional outcomes, and advance sustainable development goals [52].

Research Directions on Millets for Health and Sustainability

Precision Nutrition and Millet-Based Personalized Diets

Future research must concentrate on discerning the differences in glycemic index, polyphenol composition, and mineral bioavailability across various millet types to formulate individualized nutrition strategies aimed at managing diabetes, obesity, and metabolic syndrome. The incorporation of nutrigenomics with millet consumption could significantly augment targeted health benefits.

Gut Microbiome Modulation and Mental Health

Millets are abundant in dietary fiber, resistant starch, and polyphenols, which have the potential to selectively stimulate beneficial gut microbiota. Future clinical research should investigate the gut-brain axis, examining the effects of fermented and whole millet diets on mental health outcomes, including stress, anxiety, and cognitive function [53].

Biofortification and Genetic Improvement

Utilizing advanced breeding techniques and genomic tools to enhance millets with iron, zinc, calcium, and essential amino acids is essential for combating global micronutrient deficiencies. Research focusing on climate-resilient, nutrient-dense genotypes is crucial in the context of evolving climatic conditions. [54]

Millet-Based Functional and Therapeutic Foods

There is significant potential for the development of millet-based functional food products, including low-glycemic index snacks, gluten-free bakery items, probiotic drinks, and nutraceutical formulations. It is essential for future research to incorporate human clinical trials to substantiate the therapeutic claims associated with these foods, particularly concerning diabetes management, cardiovascular health, and cancer prevention.

Optimization of Processing Technologies

Processing techniques such as malting, fermentation, extrusion, and germination have the potential to greatly enhance nutrient bioavailability and decrease antinutritional components. Future research should focus on optimizing affordable and scalable processing technologies that are applicable to both rural and industrial settings [55].

Millets in Climate-Smart and Low-Carbon Food Systems

Millets exhibit a reduced carbon footprint, enhanced water-use efficiency, and exceptional stress tolerance when compared to major cereals. Future interdisciplinary research is essential to quantify their contribution to climate-smart agriculture, sustainable food systems, and carbon-neutral diets, as highlighted by [56].

Public Health Nutrition and Policy Integration

Long-term intervention studies are essential to assess the effects of incorporating millet into public nutrition programs, such as mid-day meals, the Integrated Child Development Services (ICDS), and food security schemes, on malnutrition, anemia, and child growth metrics. Policy-oriented research can facilitate widespread adoption [57]. Additionally, future research should examine sensory quality, consumer perceptions, and market obstacles that affect millet consumption. Innovative products that align with modern dietary habits could significantly boost millet demand in urban and global markets [58].

Conclusion

Millets serve as a critical intersection of nutrition, health advancement, and sustainability, establishing their significance in future food systems. This review emphasizes that both major and minor millets are abundant in dietary fiber, essential minerals, high-quality proteins, and a variety of bioactive compounds, which together enhance their substantial therapeutic potential in managing metabolic disorders, promoting cardiovascular and gut health, and alleviating micronutrient deficiencies.

The presence of antinutritional factors can restrict the bioavailability of nutrients; however, both traditional and modern processing methods, such as soaking, germination, fermentation, malting, extrusion, and decortication, have been proven to markedly improve nutritional quality, functional properties, and consumer acceptability. From an agricultural standpoint, the climate resilience, low input requirements, and adaptability of millets render them exceptionally suitable for sustainable and climate-smart farming systems, particularly in regions that face resource constraints and are prone to drought. Incorporating millets into diverse cropping systems enhances soil health, biodiversity, and rural livelihoods while simultaneously advancing food and nutritional security.

Future developments in biofortification, personalized nutrition, functional food innovation, and enhanced processing technologies present promising opportunities to enhance the role of millets in public health nutrition and global markets. To integrate millets into contemporary diets, it will be essential to bolster policy support, raise consumer awareness, and foster market-driven innovation. Ultimately, millets are increasingly recognized not only as traditional grains but as scientifically supported, sustainable functional foods with substantial potential to tackle modern challenges in health, nutrition, and environmental sustainability.

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