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Millets as Sustainable Functional Food Ingredients: From Traditional Foods to Next-Generation Products

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Abstract

Millets are increasingly recognized as sustainable functional food ingredients because they combine nutritional value with adaptability to challenging agricultural environments. Finger millet, pearl millet, foxtail millet, little millet, barnyard millet, and proso millet provide dietary fibre, proteins, minerals, phenolic compounds, vitamins, and other bioactive constituents. Traditionally consumed as porridges, flatbreads, fermented foods, and beverages, millets are now being incorporated into modern products such as gluten-free bakery foods, plant-based beverages, breakfast cereals, snacks, protein products, and functional formulations. Their relatively low water requirements, tolerance to environmental stresses, and suitability for diverse farming systems further strengthen their sustainability potential. Modern processing technologies, including germination, fermentation, extrusion, enzymatic treatment, and encapsulation, can improve digestibility, bioavailability, sensory quality, and product functionality.

Keywords: *Millets, functional foods, sustainable nutrition, traditional foods, bioactive compounds, food processing, climate-resilient crops.*

1. Introduction

The global food system faces simultaneous challenges involving population growth, climate change, resource scarcity, nutritional deficiencies, and increasing demand for sustainable foods. Diversification of agricultural production and greater utilization of climate-resilient crops are therefore important components of future food security. Millets have attracted renewed attention in this context because they can provide substantial nutritional value while being cultivated under relatively harsh environmental conditions [1]. Major millets include finger millet, pearl millet, foxtail millet, little millet, barnyard millet, proso millet, and kodo millet. These cereals are important sources of carbohydrates, proteins, dietary fibre, minerals, vitamins, phenolic compounds, flavonoids, and other phytochemicals [2]. Millets have traditionally been consumed in numerous forms, including porridges, flatbreads, fermented beverages, steamed foods, and snacks. Contemporary food science is expanding these applications by converting millet grains into flours, protein ingredients, plant-based beverages, extruded foods, fermented products, and functional formulations.

2. Nutritional and Functional Characteristics

Millets provide complex carbohydrates and dietary fibre, while their protein content varies according to species and cultivar. Several millet species also contain important minerals such as calcium, iron, magnesium, phosphorus, and zinc. Finger millet is particularly recognized for its calcium content, whereas pearl millet provides relatively high levels of protein and minerals. Small millets contain diverse phenolic compounds that contribute to antioxidant activity [3].

Table 1. Functional characteristics and potential applications of major millets

Millet	Important characteristics	Potential food applications
Finger millet	Calcium, fibre, phenolics	Bakery products, beverages, porridges
Pearl millet	Protein, iron, zinc, fibre	Flatbreads, snacks, protein foods
Foxtail millet	Fibre, protein, phytochemicals	Breakfast foods, beverages
Little millet	Fibre, minerals, phenolics	Functional flour and snacks
Barnyard millet	Fibre, minerals, complex carbohydrates	Gluten-free foods
Proso millet	Protein, minerals, carbohydrates	Cereals and plant beverages
Kodo millet	Fibre and phytochemicals	Functional foods and flour

The functional potential of millets is associated with their dietary fibre, phenolic compounds, slowly digestible carbohydrate fractions, and other bioactive constituents. However, the nutritional characteristics of the final food depend strongly on processing and formulation.

3. Sustainability Advantages of Millets

One of the strongest arguments for increasing millet utilization is their environmental adaptability. Many millet species can grow under conditions of limited rainfall and relatively poor soils, making them suitable for regions where water-intensive crops are difficult to cultivate [4]. Millets can contribute to agricultural diversification and reduce dependence on a limited number of major cereals. Their integration into crop rotations and diversified farming systems may support soil and agroecosystem resilience. Their sustainability value, however, should not be generalized solely from their low water requirements. Environmental impacts also depend on cultivation practices, fertilizer use, transportation, processing, packaging, and consumption patterns. Life-cycle assessment is therefore needed to quantify the sustainability of specific millet-based products.

4. Traditional Millet Foods

Traditional millet foods provide an important foundation for modern product development. Porridges and flatbreads are widely consumed in millet-growing regions, while fermented millet foods and beverages represent longstanding examples of microbial processing. Traditional processing methods such as soaking, germination, fermentation, roasting, and malting can modify nutritional properties. These processes may reduce selected antinutritional factors, improve digestibility, and alter the availability of phenolic compounds [5]. Traditional knowledge can therefore provide useful models for developing modern functional foods while maintaining culturally familiar ingredients and processing concepts.

5. From Traditional Foods to Next-Generation Products

5.1 Millet-Based Beverages

Millet milk is an emerging plant-based beverage prepared by soaking, wet milling, filtration, and stabilization of millet grains. Germination, enzymatic hydrolysis, homogenization, and fermentation may be incorporated to improve texture, digestibility, and functional characteristics. Millet beverages can also be fortified with calcium, vitamin D, vitamin B12, plant proteins, fruits, probiotics, or prebiotic ingredients to create specialized functional products.

5.2 Bakery and Gluten-Free Products

Millet flour is increasingly incorporated into bread, biscuits, cakes, crackers, and other bakery products. Because millets are naturally gluten-free, they are useful ingredients in gluten-free product development. However, the absence of gluten can reduce dough elasticity and bread volume. Blending millet flour with other gluten-free ingredients, hydrocolloids, proteins, or fibre sources can improve technological characteristics.

5.3 Extruded and Convenience Foods

Extrusion provides an efficient method for converting millet flour into ready-to-eat snacks, breakfast cereals, and expanded products. It combines cooking and shaping and can improve convenience and shelf stability. Extruded millet products can also be formulated with pulses, seeds, fruits, vegetables, and plant proteins to increase nutritional diversity.

5.4 Fermented and Functional Products

Fermentation can enhance the nutritional and functional characteristics of millet foods. Microbial activity may reduce phytate, modify proteins and carbohydrates, and transform phenolic compounds [6]. Fermented millet beverages, yoghurt-like products, porridges, and functional bakery products are therefore promising areas for innovation.

Table 2. Emerging millet-based products and their development potential

Product category	Key technology	Functional opportunity
Millet milk	Wet milling, homogenization, fortification	Plant-based nutrition
Fermented beverage	Controlled fermentation	Microbial and metabolic functionality
Millet bread	Flour blending and baking	Gluten-free nutrition
Extruded snacks	Extrusion cooking	Convenient functional foods
Millet protein products	Protein concentration and texturization	Plant-based protein
Germinated millet foods	Controlled germination	Improved nutrient accessibility
Millet-based breakfast cereals	Extrusion/flaking	Fibre-rich convenience foods
Functional millet powders	Drying and milling	Ingredient fortification

6. Processing Strategies for Functional Enhancement

Processing plays a central role in converting millet into functional food ingredients. Germination activates endogenous enzymes and can improve the availability of selected nutrients and phytochemicals. Fermentation can reduce antinutritional factors and generate organic acids and other metabolites. Enzymatic processing is particularly useful for beverages because millet starch can cause excessive viscosity. Controlled hydrolysis can improve flow properties and mouthfeel.

Extrusion can improve digestibility and create convenient food structures, although high temperatures may affect sensitive nutrients. Encapsulation represents another emerging approach for protecting millet-derived bioactive compounds or incorporating additional functional ingredients. Such technologies may improve stability during storage and digestion.

7. Health-Promoting Potential

The consumption of millet-based foods may contribute to dietary fibre intake and provide minerals and phytochemicals.

Dietary fibre can support gastrointestinal health and influence glucose and lipid metabolism. Phenolic compounds possess antioxidant properties and may interact with pathways associated with oxidative stress and inflammation [3]. Millet-based foods have also been investigated for their potential role in glycaemic management. Their fibre content and carbohydrate characteristics may influence starch digestion and glucose release. However, these effects depend strongly on the degree of processing and product formulation. Importantly, functional claims should be based on appropriate evidence. Antioxidant activity observed in chemical assays does not necessarily demonstrate a clinical benefit. Human intervention studies are needed to establish the physiological effects of specific millet foods.

8. Challenges and Future Opportunities

Several challenges must be addressed to achieve wider utilization of millet as a functional food ingredient. Raw materials vary in nutritional composition and processing characteristics according to species, cultivar, growing conditions, and storage. Sensory acceptance is also critical. Millet products may develop characteristic earthy, bitter, or astringent flavours, particularly when phenolic-rich fractions are retained. Product formulation and appropriate processing are necessary to balance nutritional value with consumer preference.

Future research should focus on standardized millet ingredients, improved processing technologies, bioavailability studies, and clinical validation. Combining millets with legumes, seeds, fruits, probiotics, and other functional ingredients could create nutritionally balanced products. The development of local processing systems may also provide economic opportunities for farmers and rural communities. Greater integration of traditional knowledge with modern food technology could facilitate the development of culturally appropriate, sustainable, and commercially viable millet foods.

9. Conclusion

Millets represent an important group of sustainable functional food ingredients with applications extending from traditional foods to next-generation products. Their nutritional composition, bioactive constituents, environmental adaptability, and suitability for diverse processing systems make them valuable for future food development. Modern technologies such as germination, fermentation, extrusion, enzymatic treatment, homogenization, and encapsulation can improve their nutritional accessibility, functionality, and sensory characteristics. Millet milk, fermented foods, gluten-free bakery products, snacks, breakfast cereals, and plant-based protein products offer promising commercial opportunities. Future research should integrate nutritional science, food technology, sustainability assessment, and clinical evidence to ensure that millet-based products deliver measurable health and environmental benefits. Greater utilization of millets could consequently support both dietary diversification and the transition toward more resilient and sustainable food systems.

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