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Millet-Derived Bioactive Compounds and Their Role in the Development of Functional Foods

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Abstract

Millets are increasingly recognized as valuable sources of bioactive compounds with potential applications in functional food development. In addition to carbohydrates, proteins, dietary fibre, vitamins, and minerals, millet grains contain phenolic acids, flavonoids, tannins, phytosterols, tocopherols, and other phytochemicals. These compounds exhibit antioxidant and other biological activities and may contribute to the health-promoting properties of millet-based foods. Their concentration and bioavailability vary considerably among millet species, cultivars, growing conditions, and processing methods. Conventional and emerging technologies such as germination, fermentation, malting, extrusion, enzymatic treatment, and green extraction can modify the concentration and accessibility of millet-derived bioactive compounds. Incorporating these compounds into beverages, bakery products, snacks, breakfast foods, and other functional formulations offers opportunities for nutritional diversification.

Keywords: *Millets, bioactive compounds, phenolic acids, flavonoids, functional foods, antioxidants, phytochemicals.*

1. Introduction

Millets are traditional cereal grains that have received increasing scientific attention because of their nutritional quality, environmental adaptability, and potential health benefits. Major species include finger millet, pearl millet, foxtail millet, little millet, barnyard millet, proso millet, and kodo millet. These grains provide carbohydrates, proteins, dietary fibre, minerals, and a diverse range of phytochemicals [1]. The bioactive fraction of millets includes phenolic acids, flavonoids, tannins, phytosterols, tocopherols, and other compounds. Many of these constituents are associated with antioxidant activity and may influence metabolic, inflammatory, and gastrointestinal processes [2]. Consequently, millet grains are increasingly being investigated not only as sources of nutrients but also as functional ingredients. The functional value of millet-derived compounds depends on their concentration, chemical structure, stability during processing, bioaccessibility, absorption, and metabolism. Understanding these factors is essential for converting promising laboratory findings into nutritionally meaningful food products.

2. Major Bioactive Compounds in Millets

Phenolic compounds represent one of the most extensively studied groups of millet bioactives. Phenolic acids such as ferulic, caffeic, p-coumaric, and syringic acids occur in free, conjugated, or bound forms. Their distribution differs among millet species and cultivars. Flavonoids constitute another important group and include compounds with antioxidant and metal-chelating properties. Tannins are particularly relevant in some pearl millet and other varieties. Although tannins may contribute to antioxidant capacity, high concentrations can interact with proteins and minerals and may reduce nutritional availability. Millets also contain phytosterols and tocopherols. These lipid-associated compounds contribute to the nutritional quality of millet grains and may provide additional biological functionality. The overall bioactive profile is therefore determined by the combined action of several classes of compounds rather than by a single constituent.

Table 1. Major millet-derived bioactive compounds and their functional food relevance

Bioactive group	Representative compounds	Potential functional relevance	Food applications
Phenolic acids	Ferulic, caffeic, p-coumaric acids	Antioxidant and protective activity	Bakery foods, beverages, functional flour
Flavonoids	Quercetin, rutin and related compounds	Antioxidant and metabolic potential	Beverages, cereals, snacks
Tannins	Condensed tannins	Antioxidant potential; may affect nutrient availability	Whole-grain foods, functional formulations
Phytosterols	β-Sitosterol and related sterols	Potential lipid-related benefits	Millet oils, cereals, snacks
Tocopherols	α-, γ-tocopherol	Antioxidant activity and lipid protection	Oils and grain-based foods
Dietary fibre-associated compounds	Bound phenolics and fibre complexes	Gut-health and antioxidant potential	Fibre-rich foods, bakery products
Bioactive peptides	Protein-derived peptides	Potential antioxidant and metabolic activities	Fermented and protein-rich products

3. Antioxidant and Health-Related Potential

Millet phenolic compounds have demonstrated antioxidant activity in chemical and experimental systems. They can scavenge reactive species and participate in mechanisms that influence oxidative processes [3]. However, antioxidant capacity measured in vitro should not be directly interpreted as evidence of clinical efficacy. Some millet-derived compounds have also been investigated for potential anti-inflammatory, antihyperglycaemic, antihypertensive, and lipid-modulating effects. Dietary fibre and phenolics may act together by influencing carbohydrate digestion, intestinal fermentation, and microbial metabolism. The gut microbiota may play an important role in determining the biological effects of millet phytochemicals. Bound phenolic compounds that are poorly absorbed in the small intestine may reach the colon, where microbial metabolism can generate smaller phenolic metabolites. These metabolites may have biological properties different from those of the original compounds [4]. Millet proteins may also serve as precursors for bioactive peptides. Fermentation and enzymatic hydrolysis can release peptides with potential antioxidant or enzyme-inhibitory activities. Further research is necessary to establish their stability during digestion and physiological relevance.

4. Effect of Processing on Bioactive Compounds

Processing has a major influence on the concentration and bioaccessibility of millet-derived bioactives. Milling can redistribute compounds between bran, germ, and endosperm fractions. Excessive refining may remove phenolic-rich outer layers and reduce the overall phytochemical content. Germination can activate endogenous enzymes and modify the chemical composition of the grain. It may increase the availability of certain phenolic compounds while reducing selected antinutritional factors [5]. Fermentation is particularly promising because microbial enzymes can release bound phenolics and transform existing compounds. Fermented millet products may therefore show altered phenolic profiles and increased antioxidant capacity. Thermal processing produces more complex effects. Roasting and extrusion may increase the release of some bound compounds but can also degrade heat-sensitive phytochemicals. The effect depends on temperature, processing time, moisture content, and the specific millet variety.

5. Extraction and Recovery of Millet Bioactive Components

The recovery of bioactive compounds from millet fractions provides an opportunity to develop concentrated functional ingredients. Conventional solvent extraction has been widely used for phenolic compounds, but newer approaches seek greater efficiency and reduced environmental impact. Ultrasound-assisted extraction, microwave-assisted extraction, enzyme-assisted extraction, and other green technologies can improve the recovery of phenolic compounds while potentially reducing solvent consumption [6]. Extracted millet bioactives may be incorporated into functional beverages, bakery products, nutritional powders, and other formulations. However, extraction can alter the natural food matrix, and concentrated extracts require appropriate safety, stability, and dosage evaluation.

6. Incorporation into Functional Foods

Millet-derived bioactive compounds can be delivered through whole-grain foods or concentrated ingredients. Whole-millet products have the advantage of providing bioactives together with fibre, proteins, minerals, and complex carbohydrates. Bakery products are among the most practical applications. Millet flour can be incorporated into bread, biscuits, crackers, and other products to increase nutritional diversity. Millet-based beverages provide another opportunity, particularly when combined with fruits, plant proteins, probiotics, or other functional ingredients. Extruded snacks and breakfast cereals can also be formulated using millet flour and bioactive-rich fractions. Appropriate processing conditions are essential to preserve desirable phytochemicals while achieving acceptable texture and flavour.

7. Challenges and Future Perspectives

Despite considerable potential, several challenges remain. Bioactive content varies substantially according to millet species, genotype, geographical origin, agricultural conditions, maturity, and storage.

Standardization is therefore essential for reproducible functional food formulations. Bioavailability is another major consideration. A high concentration of phenolic compounds in a raw grain does not necessarily indicate high absorption or biological activity. Future research should emphasize gastrointestinal digestion, cellular uptake, metabolism, and human intervention studies. Sensory characteristics must also be considered. Phenolic-rich fractions may introduce bitterness or astringency, limiting their inclusion levels in foods. Encapsulation and controlled-release systems may provide solutions by protecting bioactives and reducing undesirable sensory effects. Future product development should focus on the combined use of millet bioactives with complementary ingredients such as legumes, fruits, seeds, probiotics, and prebiotic fibres. Such combinations could produce foods with multiple nutritional and functional benefits.

8. Conclusion

Millet grains are valuable sources of diverse bioactive compounds, including phenolic acids, flavonoids, tannins, phytosterols, tocopherols, and protein-derived peptides. These compounds contribute to the functional potential of millet-based foods and have demonstrated antioxidant and other biological activities in experimental studies. Processing technologies such as germination, fermentation, enzymatic treatment, extrusion, and green extraction can modify the concentration and accessibility of these constituents. Incorporation of millet bioactives into beverages, bakery products, snacks, cereals, and other functional foods provides opportunities for developing nutritionally enriched products. Nevertheless, greater attention to standardization, bioavailability, sensory quality, safety, and clinical validation is required. Future research integrating food chemistry, processing technology, microbiome science, and human nutrition could establish millet-derived bioactives as important ingredients for next-generation functional foods.

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