



Millets on the Rise: Why Ancient Grains Are Shaping Modern Agriculture and Food Processing

*Karishma Verma

College of Food Technology, K. K. Wagh, Nashik, Maharashtra, India

*Corresponding Author's email: vermakarishma1003@gmail.com

Millets, among the oldest cultivated cereal crops in human history, are experiencing a remarkable global resurgence owing to their outstanding nutritional profiles, environmental resilience, and suitability for diverse food processing applications. These small-seeded grasses, classified into major and minor varieties, have sustained populations in arid and semi-arid regions of Asia and Africa for millennia and are now being recognized as critical tools for addressing contemporary challenges related to food security, climate change, and diet-related chronic diseases. The United Nations' declaration of 2023 as the International Year of Millets has further catalysed global interest in millet research, cultivation, and processing. This article examines the agronomic significance, nutritional composition, health benefits, and processing transformations associated with millets, drawing on recent Scopus-indexed research. The evidence strongly supports the positioning of millets as indispensable components of sustainable modern agriculture and innovative food systems.

Introduction

The global food system today faces a convergence of challenges, including rapid population growth, escalating climate change impacts, persistent malnutrition, and a rising burden of non-communicable diseases. Against this backdrop, millets have re-emerged as strategically important crops that were long overlooked in favour of high-yielding staples such as wheat and rice introduced during the Green Revolution. Millets are small-seeded grasses belonging to the Poaceae family and are broadly categorised into major millets, which include pearl millet (*Pennisetum glaucum*), finger millet (*Eleusine coracana*), and sorghum (*Sorghum bicolor*), and minor millets, including foxtail millet (*Setaria italica*), little millet (*Panicum sumatrense*), barnyard millet (*Echinochloa* spp.), kodo millet (*Paspalum scrobiculatum*), and proso millet (*Panicum miliaceum*) (Sharma et al., 2024). These crops are widely cultivated across marginal and degraded lands and have the capacity to thrive under harsh environmental conditions, including drought, high temperatures, and nutrient-poor soils, where conventional cereals are unable to perform adequately (Sharma et al., 2024).

According to Gowda et al. (2022), billions of people worldwide are currently experiencing food insecurity and malnutrition, and the United Nations has set a global target to end hunger by 2030, yet achieving that target remains distant owing to the combined effects of climate change, population growth, and economic slowdowns. Millets, described as nutri-cereals, are abundant sources of essential macronutrients and micronutrients, including carbohydrates, proteins, dietary fibre, lipids, and phytochemicals, which position them as powerful nutritional allies in this ongoing fight against food insecurity (Gowda et al., 2022). Furthermore, their inherent drought tolerance, low input requirements, and short crop cycle render them particularly valuable for smallholder farmers cultivating in resource-limited environments.



(<https://kitchenkathukutty.wordpress.com/2015/04/26/millet/>)

Khan et al. (2025) noted that millets are gaining renewed interest as commonly underexplored foods with niche potential to address multiple intersecting issues in food, health, and sustainability. Their rich nutritional profiles, low glycemic index, high dietary fibre content, and significant bioactive compound content make them suitable for individuals managing diabetes, metabolic diseases, and digestive disorders (Khan et al., 2025). The breadth of evidence now available from food science, agronomy, and nutrition sciences makes a compelling case for the systematic integration of millets into both modern agricultural strategies and food processing industries. The following sections trace this evidence from field to food system, covering millet diversity, agronomic advantages, nutritional attributes, health implications, processing technologies, and emerging challenges.

Millet Diversity and Global Agricultural Significance

Millets represent a diverse group of crops adapted to a wide range of climatic and soil conditions, making them among the most geographically versatile cereal crops on the planet. Globally, millet crops are cultivated on 718 lakh hectares, with India alone accounting for 138 lakh hectares (Sharma et al., 2024). The 2022 global production reached 304.8 lakh metric tons, with India contributing 120 lakh metric tons, equivalent to approximately 39% of the world total, followed by Nigeria with 11% and China with 9% (Sharma et al., 2024). These figures reflect a renewed global momentum in millet agriculture, particularly as policy frameworks and research programmes increasingly prioritise these crops in the context of food system resilience.

Yousaf et al. (2021) observed that millet production has been steadily increasing in recent decades to meet the dietary requirements of a growing global population, and that millets are an excellent source of all essential nutrients including protein, carbohydrates, fat, minerals, vitamins, and bioactive compounds. Their cultivation practices are also diverse and adaptive, as millets are incorporated into various cropping systems including rotation, intercropping, relay cropping, mixed cropping, and strip cropping with pulses, cereals, vegetables, and oilseeds (Sharma et al., 2024). This versatility makes them important contributors not only to household food security but also to broader agroecological stability and rural incomes.

Mukherjee et al. (2025) pointed out that millets flourish across a wide range of climatic and soil conditions, particularly in marginal and degraded lands, exhibiting remarkable resilience to various environmental stresses. Their ability to thrive under challenging

conditions with minimal water and fertility requirements makes them an invaluable resource for sustainable agriculture, especially in drought-prone areas and soils affected by acidity, salinity, or aluminium toxicity (Mukherjee et al., 2025). Due to these characteristics, millets have been aptly termed as miracle grains.

Agronomic Resilience and Climate Adaptation

One of the most compelling arguments for the wider adoption of millets lies in their superior agronomic resilience to climate change-induced stresses. As C4 plants, millets possess enhanced photosynthetic efficiency and recognised low carbon and water footprints, and they exhibit strong adaptability to diverse ecological conditions, enabling them to thrive across arid, semi-arid, subtropical, and tropical climates (Mukherjee et al., 2025). Unlike rice, wheat, and maize, which together account for nearly 80% of global food consumption and require intensive inputs while remaining highly vulnerable to climatic fluctuations, millets can sustain their productivity under conditions that would devastate conventional staples.

Sharma et al. (2024) detailed that the peculiar phenotypic traits of millets, such as their small leaf areas, thickened cell walls, dense root systems, and short life cycles, contribute directly to their stress tolerance. The large root length and decreased shoot length observed in little millet stimulate drought resistance, while the large or dense root hairs and high root biomass of foxtail millet similarly improve its ability to withstand water deficit conditions (Sharma et al., 2024). These physiological adaptations collectively enable millets to be cultivated across a diverse altitude range, from 60 to 3,500 metres above sea level, and even on marginal lands where other crops struggle to survive (Mukherjee et al., 2025).

Millet cultivation also contributes positively to environmental sustainability beyond mere climate resilience. Sharma et al. (2024) noted that millet crops contribute to reducing carbon emissions, sequestering carbon, and mitigating climate change effects due to their lower fertiliser input and harvesting machine requirements. The cultivation of millets plays a critical role in reducing soil loss, improving soil fertility, and supporting biodiversity conservation, all of which are essential attributes for sustainable land management in an era of accelerating ecological degradation (Sharma et al., 2024). Gowda et al. (2022) further noted that millets can thrive in less productive soil conditions compared to other cereal crops, which allows farmers in resource-scarce environments to achieve viable yields without heavy reliance on costly agrochemical inputs.

Nutritional Composition of Millets

The nutritional attributes of millets constitute a strong scientific basis for their inclusion in modern diets and food formulations. Millets are rich in dietary fibre, proteins, essential vitamins, and minerals including iron, calcium, and magnesium, as well as a wide array of bioactive compounds such as flavonoids, phenolic acids, and carotenoids (Sharma et al., 2024). Yousaf et al. (2021) confirmed that millets are an excellent source of all essential nutrients, including protein, carbohydrates, fat, minerals, vitamins, and bioactive compounds, and that their nutrient-rich profile positions them as a viable and superior alternative to major cereals.

Khan et al. (2025) provided a comprehensive account of millet nutritional composition, highlighting that millets are highly nutritious and health-promoting foods characterised by their rich nutrient profiles, low glycemic index, high dietary fibre, and significant bioactive compound content. Among minerals, finger millet is particularly notable for its exceptionally high calcium content, which has significant implications for the prevention of osteoporosis and the support of bone health, especially in populations with limited access to dairy products (Mukherjee et al., 2025). Pearl millet, on the other hand, is recognised for its high iron and zinc content, making it a key resource in the fight against micronutrient deficiency, which affects more than two billion people globally (Gowda et al., 2022).

The protein quality of millets is also noteworthy. Yousaf et al. (2021) reported that millets are an excellent source of all essential nutrients, including protein, carbohydrates, fat, minerals, vitamins, and bioactive compounds, and their bioactive peptides, xylooligosaccharides, and phenolic compounds add significant nutritive value and provide

protection against various degenerative diseases. Furthermore, the gluten-free nature of millets makes them a highly suitable dietary option for individuals with celiac disease or gluten intolerance, a segment of the global population that is increasingly seeking wheat alternatives (Khan et al., 2025). The plentiful polyunsaturated fatty acids present in millet oil are also beneficial in the management of chronic heart diseases, further broadening the health appeal of these crops (Yousaf et al., 2021).

Health Benefits and Disease Prevention

The health-promoting properties of millets extend well beyond their macronutrient and micronutrient content, encompassing a broad spectrum of functional bioactivities that have attracted significant scientific attention. Khan et al. (2025) established that millets are functional foods with the potential to promote sustainable agriculture and enhance health because of their high fibre content, antioxidant capacity, and anti-inflammatory properties, and that they are particularly valuable in supporting blood glucose regulation and metabolic health. Their low glycemic index is a key characteristic, as it enables a slower and more sustained release of glucose into the bloodstream, which is beneficial for individuals managing diabetes and metabolic syndrome. Mukherjee et al. (2025) reported that millets are rich sources of essential macronutrients, micronutrients, dietary fibres, essential amino acids, minerals, antioxidants, trace elements, proteins, lipids, and carbohydrates. These compounds collectively confer protective effects against a range of chronic and non-communicable diseases. Finger millet, in particular, has been associated with the ability to tackle lifestyle disorders, chronic diseases, and nervous system dysfunction due to the elevated presence of calcium, iron, and essential amino acids (Mukherjee et al., 2025). The health benefits extend to cardiovascular protection through lipid regulation, gut health promotion through prebiotic dietary fibre, and potential anticarcinogenic activity through antioxidant phenolics. Gowda et al. (2022) highlighted that nutritionally, millet grains provide significant amounts of energy, dietary fibre, calcium, iron, zinc, lipids, and quality proteins, offering sustenance and food security to vulnerable communities. These properties are particularly important for women and children, who are disproportionately affected by micronutrient deficiencies in low-income settings. In addition, millets have in-built tolerance-related characteristics that further make them a dependable dietary resource even as climatic variability reduces the availability of other food crops (Gowda et al., 2022). The convergence of nutritional richness with agronomic reliability makes millets uniquely positioned to address both food quantity and food quality challenges simultaneously.

Processing Technologies and Nutritional Changes

Food processing plays a decisive role in determining the final nutritional value, palatability, digestibility, and shelf life of millet-based products. A broad spectrum of processing techniques is applied to millets, ranging from traditional primary methods to advanced modern technologies. Gowda et al. (2022) categorised primary processing techniques as including dehulling, soaking, germination, roasting, drying, polishing, and milling, which are carried out to make millets fit for human consumption. Secondary processing methods such as fermenting, parboiling, cooking, puffing, popping, malting, baking, flaking, and extrusion are subsequently employed to develop value-added processed food products. Among the various traditional techniques, germination and fermentation have emerged as particularly effective in enhancing millet nutrition. Gowda et al. (2022) concluded that germination and fermentation showed a positive improvement in the overall nutritional characteristics of millets, whereas excessive dehulling, polishing, and milling resulted in a reduction of dietary fibre and micronutrients. Yousaf et al. (2021) supported this finding, noting that processing methods, with the exception of cooking, generally improved starch and protein digestibility in millets. These processes achieve their effects by breaking down complex starches into simpler soluble sugars, reducing antinutritional factors, and increasing the bioavailability of minerals and amino acids. Khan et al. (2025) confirmed that fermentation, soaking, and sprouting reduce anti-nutrients while boosting nutrient bioavailability, and that these methods are valuable tools for the food industry

to enhance the nutritional quality of millet-based products. At the same time, challenges persist in millet product development, particularly with regard to texture, shelf life, and consumer appeal. These limitations underscore the importance of continued research in optimising processing parameters to retain the maximum nutritional potential of millets while simultaneously meeting the sensory and functional requirements of modern consumers (Khan et al., 2025). Gowda et al. (2022) similarly emphasised that understanding the changes occurring in the nutrient value of millets due to processing can help the food industry, researchers, and consumers select suitable processing techniques to optimise nutrient value and increase bioavailability.

Antinutritional Factors and Their Management

Despite their impressive nutritional attributes, millets are known to contain antinutritional factors that can compromise the bioavailability of their beneficial compounds. These factors include phytates, oxalates, tannins, trypsin inhibitors, and polyphenols, which can bind essential minerals, inhibit digestive enzymes, and reduce the absorption of key nutrients when millets are consumed in raw or minimally processed forms (Khan et al., 2025). Yousaf et al. (2021) noted that processing is essential in millets as it enhances the nutritional bioavailability, organoleptic properties, and simultaneously reduces the antinutritional factors that would otherwise limit the dietary value of these grains. Yousaf et al. (2021) reported that dehulling millet grains beyond 30% leads to a substantial loss of dietary fibre, indicating that while removal of the outer hull reduces antinutrients, it must be conducted with careful calibration to preserve intact fibre fractions. Fermentation, on the other hand, is more targeted and beneficial in its effects. Gowda et al. (2022) highlighted that germination and fermentation are effective in reducing antinutritional factors while simultaneously improving nutrient content, thus representing a preferred processing approach for the development of nutritious millet-based foods. Khan et al. (2025) emphasised that despite the existence of strategies to manage antinutritional factors, challenges remain in terms of developing processing methods that are both effective and economically feasible for smallholder farmers and small-scale processors. Research directed at combining multiple processing steps, such as soaking followed by fermentation or germination followed by roasting, offers promising avenues for reducing antinutrients more comprehensively while simultaneously enhancing sensory attributes. These combined processing approaches represent an important frontier in millet food technology that can bridge traditional practices with modern nutritional science.

Value-Added Millet Products and Market Potential

The transformation of raw millets into value-added food products is a critical step in ensuring their wider market acceptance and mainstreaming into global food systems. Yousaf et al. (2021) documented that millets are processed into a wide range of food products including malted, cooked, fermented, roasted, and puffed preparations, and that their immense popularity in tribal communities extends to use in snacks, bread, puddings, and beverages, which also hold important cultural significance in many societies. As consumer preferences increasingly shift towards healthier, functional, and minimally processed foods, the market opportunity for millet-based products has expanded substantially. Sharma et al. (2024) identified that millets are versatile in value-added foods such as gluten-free flour, snacks, and fermented foods, and that their multiple functional properties have been recognised across the food and beverage industry, including in the production of weaning foods, health bars, breakfast cereals, noodles, cookies, and traditional fermented beverages. The development of such products is supported by the functional characteristics of millets, which include good water absorption capacity, emulsification properties, and gelation behaviour, all of which are desirable from a food technology standpoint. Gowda et al. (2022) noted that functional characteristics of millets are useful for designing special foods and value-added products, and that technology interventions are required to motivate both farmers and food manufacturers to adopt millets more widely. Mukherjee et al. (2025) further pointed out that the millet industry has significant potential to contribute to rural employment, household incomes, and national economies, particularly in

developing countries where millet cultivation is traditionally embedded in agricultural systems. The economic opportunity presented by the global health food trend, combined with the 2023 International Year of Millets policy push, has created a favourable environment for investment in millet processing infrastructure, research and development, and market expansion. Khan et al. (2025) underscored that research is the key to promoting millets as a modern dietary staple, and that continued innovation in processing, packaging, and product development will be decisive in expanding the consumer base for millet-based foods beyond traditional markets.

Conclusion

Millets represent a convergence of agronomic resilience, nutritional richness, and food processing versatility that makes them uniquely suited to the demands of modern agriculture and food systems. Their drought tolerance, climate adaptability, and low environmental footprint address the urgent need for sustainable crop production in an era of accelerating climate change. Simultaneously, their exceptional nutrient profiles, functional bioactive compounds, and suitability for diverse processing applications position them as powerful instruments for combating malnutrition, managing chronic disease, and meeting the growing consumer demand for healthy, gluten-free, and minimally processed foods. The convergence of scientific evidence, global policy support, and consumer interest signals that the resurgence of millets is not a temporary trend but a structural shift in how humanity approaches food, agriculture, and nutrition security. Sustained investment in research, processing technology, and inclusive value chains will be essential to realising the full potential of these ancient grains in the modern world.

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