



E-ISSN: 2709-9385  
 P-ISSN: 2709-9377  
 JCRFS 2024; 5(2): 110-115  
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[www.foodresearchjournal.com](http://www.foodresearchjournal.com)  
 Received: 22-09-2024  
 Accepted: 27-10-2024

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## Foxtail millet: Rediscovering a superfood for the 21<sup>st</sup> century

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### Abstract

Foxtail millet, a climate-resilient and nutrient-rich cereal, emerges as a promising solution for sustainable agriculture and food security. Its ability to thrive in arid and semi-arid regions with minimal water input makes it a valuable resource in the face of climate change. This article provides a comprehensive overview of foxtail millet, exploring its nutritional profile, agronomic advantages, and potential to contribute to global food security. The review also analyzes the challenges associated with its cultivation and proposes strategies to promote its wider adoption. The grain's nutritional profile, particularly its high content of protein, fiber, iron, and calcium, offers significant health benefits. By promoting the cultivation and consumption of foxtail millet, we can enhance food security, improve public health, and mitigate the impacts of climate change on agriculture.

**Keywords:** Foxtail millet, climate resilience, food security, nutrition, sustainable agriculture

### Introduction

Climate change has gradually raised the risk of food insecurity in arid and semi-arid regions due to volatile weather patterns, prolonged drought, and poor soil quality for crops. Consequently, people are experiencing scarcity of food, and this calls for more enhanced crops in terms of performance in the current challenging environments. Thus, millet, especially foxtail millet, stands as a sustainable option. Millets are energy and water-efficient crops that give high yields with low water input in stressful environments. Due to their characteristic of growing well in soils of low fertility, as well as with limited water availability, they are important in areas that face food shortages. Furthermore, the germination rate is relatively high for foxtail millet, and this grain contains the nutritional benefits of fiber, vitamins, and minerals, which boosts the nutritional value for vulnerable populations.

Organic farming, and conservation agriculture, are of maximum importance when it comes to food security, particularly concerning the effects of climate change. Since millets are an ancient cereal, they have great potential in building climate-resilient agriculture in areas where the water deficit is critical and the environment is rather unfavourable. Foxtail millet, due to its climate resilience and nutritive value, can be a major player in promoting sustainable agriculture and food security in the world.

### Nutritional Profile and Health Benefits

Foxtail millet, a minor millet species, has been receiving attention for its nutritional values and the viability of the plant in problem soils. Being among the gluten-free plants and also being able to survive in drought conditions, foxtail millet has several nutritional advantages in addition to rice and wheat. Foxtail millet contains about 12-15% protein, 65-75% carbohydrate content 15-20% dietary fiber, and is rich in some micronutrients <sup>[1]</sup>.

The beneficial characteristics of foxtail millet include its high fiber value, which helps to support digestion and regulate cholesterol levels. It is also rich in protein. While plant proteins are usually incomplete, lacking certain essential amino acids, this seed is a good source of such proteins. Foxtail millet contains amino acids such as methionine and cysteine, which are limiting in other cereal grains such as wheat, making it a good complementary protein for legumes or animal proteins <sup>[2]</sup>.

Tripathi's work pointed out that foxtail millet is rich in minerals like iron (Content is 2.5 mg per 100 g) and calcium (80 mg per 100 g). This mineral content makes this grain nutritionally superior to other grains, especially for at-risk populations. Iron is a nutrient of particular importance in the prevention of anemia, and the calcium content is beneficial in

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the maintenance of bone mass. In contrast, the iron content is much lower in rice (0.3 mg of iron in 100 g), and as for wheat, though it is slightly higher than rice, it is not as rich in iron as foxtail millet. The calcium content in rice and wheat is far less than in foxtail millet, making it a far better source of these minerals.

### Comparison with Rice and Wheat

This section provides an insight into the nutraceutical value of foxtail millet and compares its nutritional composition with rice and wheat. Rice, as the primary food for more than half the world's population, is a major source of carbohydrates, while protein and micronutrient values are comparatively low. It has 2-3% protein, and its percentage

of dietary fiber, iron, and calcium is very low [3]. Due to these restrictions, people who rely heavily on rice as a staple food may lose out on essential nutrients, which is particularly concerning in regions with high incidences of malnutrition. Wheat, another widely consumed grain in the global market, is a little more nutritious than rice in terms of protein content (About 10-12 percent) and has higher levels of vitamins and minerals [4]. However, the use of wheat is restricted for some since it contains gluten, while foxtail millet is gluten-free, making it a good option for people with celiac disease or gluten intolerance. Wheat has high gluten content, which, while desirable for purposes of bread making, may not be good for those with allergies or who follow particular diets or have stomach illnesses.

Nutrient	Foxtail Millet (100 g)	White Rice (100 g)	Whole Wheat (100 g)	Barley (100 g)
Calories	378 kcal	130 kcal	340 kcal	354 kcal
Protein	12-15 g	2-3 g	10-12 g	12 g
Carbohydrates	65-75 g	28-30 g	70-75 g	73 g
Dietary Fiber	15-20 g	0.4g	12-15 g	17 g
Fat	4-6 g	0.3g	2-3g	1.5 g
Iron	2.5 mg	0.3 mg	3.6 mg	2.5 mg
Calcium	80 mg	10 mg	41 mg	29 mg
Magnesium	120 mg	12 mg	138 mg	79 mg
Vitamins (B1, B2, B3)	High (especially B3)	Low	Moderate	Moderate

Utilization of foxtail millet is somewhat restricted in terms of energy density because its carbohydrate sources of energy are not as easily broken down as those in rice and wheat, which are processed and polished in many markets around the world [5]. This lower digestibility could affect the assimilation of other micronutrients in areas where millet is the prime staple food.

### Health Benefits of Foxtail Millets

Foxtail millet has numerous nutritional values that make it a good diet for several categories of people, particularly those with diabetes complications. Due to its low glycemic index (GI: 50-55), it aids in controlling the rate of glucose release into the blood because it breaks down glucose at a slower rate than high-GI foods such as white rice and wheat [1]. This is beneficial for diabetic patients because consuming high-GI foods can cause fluctuations in blood sugar levels, making it difficult to manage the condition. Additionally, due to its relatively high fiber content, the consumption of foxtail millet is particularly beneficial for the digestive system, heart, and for managing cholesterol. Fiber ensures regular bowel habits, prevents constipation, and facilitates the growth of beneficial bacteria in the gut. It also decreases levels of bad cholesterol (LDL), which in turn decreases the risk of heart diseases and increases satiety levels that can be effective in weight control. Magnesium and potassium present in the grain help to maintain blood pressure, making it heart-healthy [6].

Foxtail millets also have high levels of antioxidant compounds, which play a role in reducing oxidative stress and inflammation [7]. These properties are useful for lowering the risk of metabolic diseases like obesity, type 2 diabetes, and cardiovascular diseases. Phenolic compounds

present in foxtail millet have the property to combat free radicals and reduce cell damage and chronic inflammation. It is important to remember that relying solely on any one grain can lead to nutrient deficiencies. For example, although foxtail millet contains vitamins and other nutrients, it does not have adequate amounts of certain vitamins and essential fatty acids, which means that other grains and a variety of foods must be eaten in conjunction with foxtail millet. Also, millet may contain goitrogens, which can interfere with iodine absorption and potentially lead to thyroid problems such as goiter. However, this can be mitigated by consuming iodine-rich foods and employing proper cooking methods such as soaking and rinsing the grains before cooking.

### Climate Resilience of Foxtail Millet

#### Adaptability to Extreme Environments

Foxtail millet (*Setaria italica*) is known for its resistance to harsh conditions such as high temperatures, water stress, and low soil fertility. This flexibility makes it a useful crop under changing climate conditions, particularly water shortage, especially where the climate is extreme and unfavorable for crop production. One of the most significant features of foxtail millet is its drought-tolerant characteristic. The crop needs about one-fourth of the water that is needed for the production of commonly consumed foodstuffs such as rice. Arab *et al.* [8] further explained that this high water use efficiency (WUE) is attributed to its root/shoot ratio and C4 photosynthesis, through which the plant can carry on its growth and production even under a limited water supply. Such characteristics make foxtail millet an important crop in water-deficit zones, particularly in the semi-arid and arid zones of the world where water availability for irrigation for other cereals is a challenge.



Source: (Singh and Prasad, 2020) [7]

Fig 1: Benefits of Millet

Foxtail millet can also grow significantly well in and around areas where temperatures are known to rise beyond 35°C. Most other cereal crops are very sensitive to heat stress, which severely affects their yield, but this is not the case for foxtail millet because of its heat tolerance characteristics [7]. The fact that it can maintain good yields when exposed to high temperatures is a definite asset, particularly in those areas that have been affected by global warming or are experiencing higher temperatures. Indeed, foxtail millet is a highly heat- and drought-resistant plant that thrives in areas with limited water supply or rainfall. Its well-established root system is adapted to draw water from deeper levels of the ground, ensuring a water supply for its growth even during periods of drought.

India is among the top producers of foxtail millet (*Setaria italica*) in the world, contributing to about 10% of global production. Comprising six agro-climatic zones, the country and its traditional millet farming system have embraced this drought-resistant cereal. The growth of foxtail millet is mainly observed in the south, with Karnataka, Tamil Nadu, and Andhra Pradesh as the primary producers [9]. These areas have preferable conditions for foxtail millet, including semi-arid conditions and well-drained soils, which allow for its growth even in places with low water availability. Karnataka is the leading producer of foxtail millet and contributes a major portion of its production to India. Tamil Nadu comes second, with farmers in the state continuing to cultivate millet crops as an important food security crop for human consumption.

India's foxtail millet production aligns with the country's efforts in encouraging the cultivation of millets, which are well adapted to climate change and have good nutritional values. The Indian government has introduced measures to increase millet production under the "National Year of Millets" advocacy because these crops are more resistant to unfavorable environmental conditions than some modern cultivars that have been introduced to farmers. India is the

leading producer of foxtail millet in the world, especially at a time when the emergence of this crop provides much-needed hope as climate-smart cereals in semi-arid zones of the world for food security [10]. Therefore, by continuing to increase millet production, India plays a crucial role in supporting world millet markets and advocating for millet-resilient agriculture.

However, it is important to acknowledge that the nutritional value and production of foxtail millet may be relatively lower than other staple cereals, such as wheat and rice [10]. But owing to its adaptability to harsh climatic conditions and its low input requirements, it is a key crop for authorities seeking to enhance food security in vulnerable regions. The consumption of foxtail millet can help farmers diversify crop production and reduce the negative impacts of climate change on agricultural production.

#### Scientific Advancements

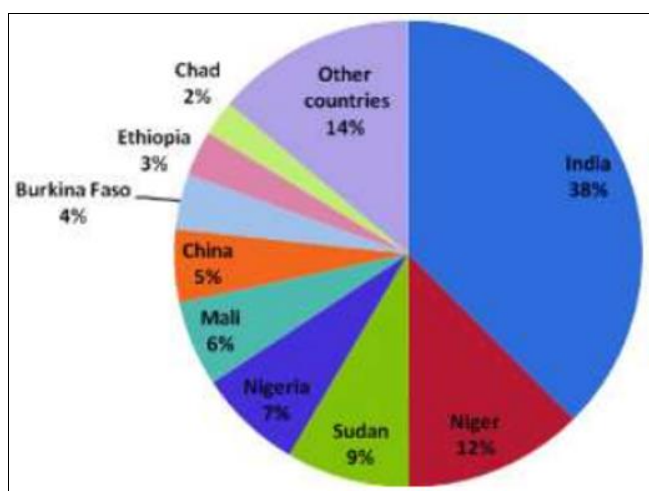
Foxtail millet is a C4 plant, meaning it utilizes a form of photosynthesis that improves the use of water and nutrients. C4 photosynthesis is a process in which carbon dioxide is first fixed into a four-carbon compound. This mechanism reduces the rate of photorespiration, making C4 plants more efficient under conditions of high light intensity, heat, and drought stress [11]. This accounts for the fact that foxtail millet is more productive with less water supply when compared to other crops and is considered the right crop to cultivate in areas where water availability is scarce. Studies comparing the photosynthetic efficiency of foxtail millet (a C4 plant) with C3 plants have shown that C4 crops possess a higher WUE. For instance, under drought conditions, C4 plants like foxtail millet have been found to have a 50% improvement in WUE compared to C3 plants [12]. This advantage is very important for millet farming, which is mostly practiced in regions that are characterized by limited water supply.



In recent years, through genomic research, geneticists have identified approximately 38,000 genes in foxtail millet, many of which contribute to stress tolerance. Gene expression maps during periods of stress reveal that genes associated with osmotic adjustment and reactive oxygen scavenging are activated under adverse conditions [7]. This research has the potential to further improve the stress tolerance and yield of foxtail millet through targeted breeding and genetic engineering approaches.

### Economic and Agricultural Importance of Foxtail Millet Global Distribution and Production

Foxtail millet (*Setaria italica*) is one of the most widely cultivated cereal crops in regions experiencing drought and semi-arid climatic conditions. It is mainly produced in a number of countries around the world, with India, China, and Ethiopia being the major producers. There is a variation of agro-climatic conditions and practices that prevail across the countries that produce foxtail millet.



Source: (Raut, et al., 2023) [13]

Fig 2: Millet Production in Different Countries

India is one of the largest producers of foxtail millet, accounting for almost 10 percent of the world's production. In 2020, the country was estimated to have produced 1.3 million tonnes of foxtail millet, produced largely in Karnataka, Tamil Nadu, and Andhra Pradesh [13]. These southern states enjoy semi-arid climatic conditions, which are best suited for millet production. India's production can be attributed to the high nutritive value of the crop, its high yield under conditions of water stress and poor soil fertility, and the various government initiatives promoting millet cultivation [24]. Numerous schemes, including the recently launched 'National Year of Millets,' have also helped in reviving millet production as a part of the government's broader climate change fight and efforts to improve soil health.

China has the largest production of foxtail millet, where it has a cultivation history of at least 5,000 years. The northern provinces of Shanxi, Hebei, and Inner Mongolia are the dominant areas where millet is grown. Chinese farmers prefer foxtail millet because it is drought-resilient and can be quickly harvested [13]. People consume it for preparing porridges and spirits; however, demand for this grain has increased due to health concerns. As this highlight, foxtail millet is an essential crop for China as a supplier and for

people all over the world who use the product in traditional diets.

However, according to Meena *et al.* [14], the current global production status shows that, out of all the millets, foxtail millet ranked fourth in 2020. Though its production has fallen behind other millets like pearl millet and sorghum, it remains important in arid and semi-arid areas. Unfortunately, similar to most crops, foxtail millet production faces challenges such as a limited market and a continuous shift from its production to other more profitable crops. This trend raises concerns about the product's future as a staple food in areas most affected by climate change.

### Agricultural Benefits

Foxtail millet crops are excellent for low-input production compared to crops such as wheat and maize, thus providing low-cost options that farmers can adopt. While wheat and maize, for instance, need high levels of fertilizer, pesticides, and irrigation to yield optimum results, foxtail millet can grow well in poorly fertile soils [15]. Because it can easily be cultivated in less fertile environments, it is well suited for regions where expensive farming chemicals and water are scarce [25]. It also has the advantage of being suitable for resource-constrained smallholder farmers who may not afford to invest in intensive farming.

The low utilization of fertilizers and pesticides in foxtail millet production offers massive advantages to the natural environment. Farmers can lower soil and water pollution resulting from the high use of chemical inputs in agriculture. Moreover, restricted use of pesticides helps to conserve the natural enemies of pests and pollinators [16]. However, it is important to note that without chemical inputs, the yield of foxtail millet may be lower compared to crops like wheat and maize that are grown with chemical fertilizers, especially under suboptimal conditions.

Although foxtail millet can be used in crop rotation to enhance soil fertility, its low market value compared to crops such as maize may lead to a low adoption rate by farmers [17]. Limited market access may also hinder its widespread cultivation, despite its agronomic advantages. Therefore, encouraging the adoption of foxtail millet into crop rotation systems will likely require stronger market pull mechanisms and greater farmer appreciation of the long-term benefits associated with sustainable millet farming.

### Market Growth and Business Opportunities

According to Kang *et al.* [18], there has been a recent rise in the consumption of foxtail millet and other millets all over the world as consumers become more aware of the nutritive value of these grains. With their high levels of fiber, protein, and micronutrients, these millets are considered "new-generation" foods, especially among the health-conscious and those who prefer gluten-free foods. The demand is further buoyed by the growing global push toward plant-based diets, which makes millet an attractive functional grain for those who want to shift from animal-based meals.

\*\*India is currently the largest producer and consumer of millets, and its domestic market share is experiencing significant growth. The global market for millet is expected to exhibit a compound annual growth rate (CAGR) of 4.60% during the period from 2023 to 2028, with the value of the millet market in this country expected to reach \$13.80 billion\*\* [13]. This growth can be attributed to increased

awareness among the population due to government campaigns promoting millet as a super food, as well as a greater understanding of the health benefits associated with millet consumption.

India has also seen a substantial increase in its export of millet. During the financial year 2021-2022, India exported 159,332.16 metric tonnes of millets, which was 8.02% more than the export of the previous financial year [13]. This rise in exports indicates an increasing demand for millet foods in various global markets, especially in Europe and the U.S., where consumers are increasingly health-conscious and seeking organic and gluten-free foods. As the global trend for healthy and sustainable foods intensifies, India's position as a major millet exporter is likely to strengthen.

### Challenges and Future Directions for Foxtail Millet Cultivation

Despite its benefits, foxtail millet cultivation faces several challenges that limit its production and consumption across the globe. These challenges fundamentally result from limited utilization, processing constraints, and lack of consumer awareness.

According to Saini *et al.* [19], foxtail millet and other millets are underutilized compared to the widely popular rice and wheat. For centuries, global agriculture has been dominated by wheat and rice, which has overshadowed the potential of millets. This can be attributed to entrenched food cultures and eating habits that favor the consumption of wheat and rice, particularly in India and China. Furthermore, farmers continue to grow these major crops due to government support, subsidies, and market forces [20]. Consequently, the modern world often marginalizes crop varieties like foxtail millet, which are considered primitive or 'minor,' despite the valuable lessons they offer for sustainable agriculture. Moreover, existing agricultural policies and subsidies often overlook millets. To encourage farmers to cultivate larger quantities of millet, government incentives and strong market demand are necessary.



Fig 3: Challenges in Millet Cultivation

**Processing Limitations:** The lack of adequate processing technology for foxtail millet and other millets poses another

challenge to their wider utilization. Although they are common crops, millets require different processing technologies compared to rice and wheat [21]. Traditional processing methods are often not suitable for millets, resulting in poor quality products and low market acceptance. Additionally, the infrastructure for processing, milling, packaging, and storing millets remains underdeveloped. This can make millets seem less refined, less convenient (They often require longer cooking times), and less appealing to consumers who are accustomed to polished grains like rice and wheat. Therefore, to increase the market acceptance of millets, it is crucial to invest in research and development of appropriate processing technologies that can produce high-quality millet products.

### Consumer Awareness

Low consumer awareness regarding the nutritional and environmental benefits of foxtail millet is a major obstacle to its widespread adoption. Despite being a good source of fiber, antioxidants, vitamins, and essential minerals, the grain is not well known for these nutrients. Efforts to promote millet as a nutritious and sustainable grain have been limited by a lack of effective advocacy and marketing strategies. Despite research highlighting the nutritional value of millets, many consumers, particularly in rural areas, continue to perceive millets as 'famine foods' or food for the poor. This perception hinders their integration into modern diets as a viable alternative to conventional cereals [22]. Moreover, governments and organizations have not adequately invested in awareness campaigns to educate the public about the health and environmental benefits of millets, such as their low input requirements and minimal environmental impact.

In the absence of specific branding and targeted advertising for millet products, consumer interest remains low. While grains like rice and wheat have been transformed into a wide array of products (flour, instant noodles, snacks, etc.), foxtail millet and other millets have not received the same attention [24]. To overcome this, creative marketing and educational campaigns are needed to highlight the versatility and benefits of foxtail millet and to dispel outdated perceptions. Until then, foxtail millet will likely remain confined to traditional and niche markets.

### Conclusion

Foxtail millet has many health benefits, owing to its high protein, fiber, and essential mineral content. It is a valuable option for special diets that involve avoiding gluten products. It is particularly beneficial for diabetics because it has a low glycemic index. It also has antioxidant properties that promote heart health. The crop is well-suited for cultivation in regions facing climate change challenges such as drought and poor soil conditions, making it appropriate for production in stressed environments. The benefits of foxtail millet are numerous: Economically, it provides livelihoods for small-scale farmers and contributes to food security in countries like India and China. Environmentally, it promotes sustainable agriculture due to its low input requirements and resilience to harsh conditions. Nutritionally, it offers a rich source of essential nutrients, contributing to improved public health.

However, to fully realize the potential of foxtail millet, several gaps need to be addressed. These include research on regional adaptation, improving yield and disease

resistance through genomic studies, enhancing market access, increasing consumer awareness, and ensuring profitability for farmers. Further research is also needed to explore its role as a sustainable agricultural technique and its contribution to food security in climate-vulnerable areas. By strengthening practices and addressing these challenges, the global adoption of millet can be significantly increased.

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