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A brief review on world of foxtail millet: From botanical characteristics to market trends

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ABSTRACT

Foxtail millet (*Setaria italica*), an ancient cereal with remarkable adaptability and nutritional richness, is gaining renewed global interest for its role in sustainable agriculture and food security. This review presents a critical synthesis of foxtail millet's botanical traits, agronomic practices, varietal advancements, nutritional benefits, post-harvest processing, and market trends. Unlike previous reviews, this study offers comparative insights into the performance of diverse improved varieties across agro-climatic zones, highlighting their influence on yield, nutrient uptake, and economic returns. It further contrasts foxtail millet's market trajectory with that of other climate-resilient grains, underscoring its potential in both domestic and export markets. By integrating findings from Indian and international studies, this paper provides a comprehensive reference for researchers, policymakers, and practitioners aiming to harness the full potential of foxtail millet in addressing climate challenges, malnutrition, and livelihood improvement.

1. INTRODUCTION

Millets are a group of small-seeded grains, primarily in Asia and Africa. They are highly nutritious, gluten-free, and resilient crops, offering various health benefits. It has been utilized as food, feed, and forage since the Neolithic era, with Pearl millet, Finger millet, and Sorghum recognized as Major millets [1], while others are categorized as minor millets. Minor millets comprise Proso millet, Foxtail millet, Little millet, Barnyard millet and Kodo millet. Small millets are renowned for their richness in protein, energy, dietary fiber, and nutraceutical properties, making them multipurpose crops often referred to as miracle-crops [1-3]. Currently, agriculture faces significant challenges due to climate change and global warming, characterized by rising temperatures, erratic rainfall patterns, and increased emissions of greenhouse gases, primarily carbon dioxide. As C_4 plants, millets can effectively utilize elevated atmospheric CO_2 levels, converting them into biomass [1,4]. Millets represent environmentally sustainable crops capable of thriving in warm and drought-prone conditions while maintaining a low carbon footprint in agriculture, thus earning them the designation of climate-smart crops.

Foxtail millet is one of the oldest cultivated millets, known for its drought tolerance and versatility in culinary applications. Its growing popularity stems from its rich nutritional profile and suitability for sustainable agriculture. Foxtail millet, belonging to the Paniceae tribe within the Poaceae [Figure 1] family, emerged through the domestication of green millet in northern China approximately 8000 years ago [5,6]. Its cultivation spans developing regions across Africa, Americas, and Asia's semiarid and arid areas [7], driven by its manifold health advantages [8]. These benefits stem from its diverse nutrient composition, including starch, protein, dietary fibers, fats, and vitamins, as well as its ability to promote low glycemic and hypolipidemic effects [6]. Moreover, foxtail millet's capacity to deliver robust yields with minimal agricultural inputs and its resilience to salinity, drought, and other stresses, further contribute to its widespread cultivation [6,8,9,10].

2. BOTANICAL CHARACTERISTICS

Foxtail millet is typically characterized by a solitary main stem or a few tillers, accompanied by robust inflorescences that mature uniformly. Upon maturity, foxtail millet plants reach a height ranging from 120 to 200 cm, with slender, erect, and foliage-rich stems. The leaves are smooth, hairless, and broadly arc-shaped, while the culms are erect and slender with hollow internodes. At the apex of the stems, a profuse panicle emerges, measuring typically between 5 and 30 cm in length, often displaying reddish or purplish hues, resembling a fox's tail [11]. Compared to other small millets such as proso millet (Pani*cum miliaceum*) and barnyard millet (*Echinochloa* spp.), foxtail millet

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exhibits more uniform flowering and maturity, which is advantageous for mechanical harvesting and synchronous yield.

Foxtail millet's inflorescence [Figure 2] adopts a compact panicle form, sometimes inclined at the apex, resembling a spike due to its abbreviated branches. Within the inflorescence, spikelets are densely arranged, interspersed with rigid bristles, each containing a solitary flower with a distinct yellow pistil. Foxtail millet typically requires 5 weeks from sowing to flowering and an additional 8–15 weeks for seed maturation [11,12]. Each inflorescence has the potential to yield numerous diminutive convex seeds, approximately 2 mm in diameter, encased within a delicate, membranous hull that facilitates easy separation during threshing. The coloration of the seeds varies significantly among different varieties [11].

Foxtail millet exhibits remarkable adaptability to a wide range of soil and climatic conditions. It thrives equally well in both tropical and temperate environments, enduring moderate to low precipitation levels and thriving at elevations up to 2000 m. While it prefers well-drained loamy soils, foxtail millet is intolerant to waterlogged conditions or extreme aridity [13]. Its exceptional ability to acclimate to diverse environmental settings makes it suitable for cultivation across a broad expanse of geographical terrains. It has a C_4 photosynthetic pathway that makes it highly efficient in water use. Its life cycle is relatively short (70–100 days), and it shows remarkable adaptability to diverse agro-climatic conditions, including drought-prone and semi-arid regions. Due to its deep root system and efficient water-use mechanism, it is suitable for dryland agriculture and climate-resilient farming systems.

3. HISTORICAL SIGNIFICANCE AND CULTIVATION

Foxtail millet holds a distinguished place as one of the earliest cultivated crops, with its origins traced back approximately 7,400–7,900 years before present in the Cishan and Peiligang ruins of the Yellow River Valley in northern China [14]. Its wild ancestor, green foxtail (*Setaria viridis*) served as the foundation for the modern cultivated variety (*Setaria italica*) [11,15,16]. In ancient China, a combination of foxtail millet and proso millet (*P. miliaceum*) cultivation was prevalent [7,17,18]. In India, major cultivation areas include Karnataka, Andhra Pradesh, Rajasthan, Madhya Pradesh, Chhattisgarh and Tamil Nadu [11]. Foxtail millet is commonly referred to by various names in India, including Kangni (Hindi), Kang (Gujarati), Navane (Kannada), Kaon dana (Bengali), Kavalai, and Kangam (Oriya), as well as Tenai (Tamil) [11].

Foxtail millet, also known as Italian millet, is believed to have undergone domestication during the Neolithic period. It stands as one of the ancient cereals cultivated across Europe and Asia, with China alone contributing over 45% of the global production [19]. Initially cultivated during the Neolithic period, foxtail millet's adaptation to cooler climates facilitated its spread, with cultivation expanding over time across various regions. Historically, its cultivation held significant cultural and economic importance, serving as a staple food crop for many communities. Its short maturation period of 70–120 days made it an attractive option for agricultural practices. Moreover, foxtail millet's nutritional profile, rich in protein, fiber, and essential micronutrients such as iron, magnesium, and phosphorus [19], further underscored its historical significance as a valuable dietary staple.

4. CROP IMPROVEMENT IN FOXTAIL MILLET

Foxtail millet has seen significant advancements in crop improvement worldwide, moving from traditional methods to modern biotechnology. Globally, traditional breeding methods like mass selection and crossbreeding initially enhanced traits such as yield and disease resistance. Later, conventional techniques like hybridization developed high-yielding varieties. Biotechnological approaches, including marker-assisted selection and genetic engineering, further improved millet by introducing traits like pest resistance and enhanced nutrition. Foxtail millet exhibits considerable genetic diversity with landraces and wild relatives preserved in gene banks such as ICRISAT and NBPGR. "In addition to Indian breeding initiatives, global programs - such as genomic research by Doust *et al.* [14] and Tang *et al*. [10] in China - have advanced the development of stress-tolerant and nutritionally enriched varieties using CRISPR and transcriptome profiling." Recent advancements in genomics have led to the identification of stress-resistant and high-yielding varieties. Breeding programs have increasingly adopted molecular markers, QTL mapping, and CRISPR-Cas genome editing for crop improvement. Countries like India and China have launched focused millet breeding initiatives to improve yield, pest resistance, and nutritional content. In India, especially in Tamil Nadu, similar strategies were employed, with regional varietal development, government initiatives and collaborations driving progress. Institutions like the Tamil Nadu Agricultural University played pivotal roles and the adoption of modern techniques promises accelerated improvements in foxtail millet varieties.

5. IMPROVED VARIETIES IN FOXTAIL MILLET

Breeding efforts have led to the development of improved varieties of foxtail millet, enhancing its cultivation and productivity. These varieties [Figure 3] exhibit specific characteristics that contribute to their superiority over traditional strains. For instance, Jyothi *et al.* [20] observed increased grain yields under rainfed conditions in Andhra Pradesh with varieties such as SiA 3088, SiA 3085, SiA 3156, and Srilaxmi. Similarly, in experiments conducted in different locations, Ramyasri *et al.* [21] noted that SiA 3156 outperformed other varieties, yielding 1290 kg/ha during the rabi season in Andhra Pradesh.

The selection of appropriate varieties is crucial for optimizing yield and quality. Studies have shown that varieties like SiA 2644 demonstrate superior performance over local and HMT-1 varieties in specific soil conditions, as observed in the southern transition zone of Karnataka [23]. Furthermore, regional variations impact variety selection, as demonstrated by Marwein *et al.* [24], who found that SiA 326 (Prasad) yielded better results than SiA 3156 in sandy loam soil in Prayag, Uttar Pradesh.

Nirmalakumari *et al*. [25] observed ATL 1 exhibits an average grain yield of 2117 kg/ha and straw yield of 2785 kg/ha under rainfed conditions, representing a 9.6% increase in grain yield and a 14.8% increase in straw yield compared to the check variety CO (Te) 7.

According to Hasemi *et al.* [26], minor millets exhibit salt stress responses across varying levels (1.5, 5.5, and 9.5 d/m). Their study in Southern Khorasan, eastern Iran, found that pearl millet from Birjand, followed by foxtail millet, displayed the highest production potential under both salt-tolerant and normal conditions. Nadeem *et al.* [27] reported that foxtail millet's root system decreases in response to low levels of nitrogen and phosphate in the soil, yet it exhibits increased biomass production and root thickness, potentially enhancing nutrient transfer. The interaction between foxtail millet and nitrogen nutrition is significant, as indicated by its response to low phosphate levels, which may regulate nitrogen transporter activity, according to Hasemi *et al.* [26].

Overall, the development of new varieties with high-yield potential, coupled with strategic breeding efforts, has contributed to the increased resilience and adaptability of foxtail millet. Short-duration varieties like SiA 3085 and SiA 3088 have gained popularity due to their suitability for major cultivated areas, while systems like the foxtail-chickpea system have enhanced income in regions like Kurnool and Andhra Pradesh. Additionally, the adoption of foxtail millet in paddy fallows, particularly short-duration varieties, is becoming increasingly popular in areas facing water limitations [22].

6. AGRONOMIC PRACTICES AND CROP MANAGEMENT

6.1. Season and Sowing

Foxtail millet is grown throughout India due to its adaptability to diverse climates. Its sowing time varies by region. In the Northern Plains and Central India, it is usually planted during the summer or kharif season from June to July after the monsoon begins. Southern states like Karnataka and Tamil Nadu cultivate it both in the kharif (June-July) and rabi (October-November) seasons. Eastern and Northeastern states like Odisha and West Bengal primarily sow it in the kharif season starting around June or July with the monsoon onset. Western states like Maharashtra and Gujarat also sow during the kharif season from June to July. Farmers time their sowing with the monsoon's arrival or when soil moisture is sufficient. Additionally, in irrigated regions, foxtail millet can be planted as a rabi crop post-monsoon [13].

6.2. Irrigation and Nutrient Management

Foxtail millet, often grown as a rainfed crop during the kharif season, requires minimal irrigation. However, in case of extended dry spells, life-saving irrigation becomes necessary, typically at 25–30 and 40–45 days after sowing [13]. Nutrient management is crucial for optimal yield. To achieve optimal productivity and preserve soil health, it is recommended to adopt integrated nutrient management (INM). Typically, this involves applying 5–10 tons of farmyard manure (FYM) along with 40 kg of N, 20 kg of P_2O_5, and 20 kg of K_2O [28,29]. Nevertheless, Kumaran and Parasuraman [30] noted that INM enhanced the grain yield of foxtail millet in Tiruvannamalai, Tamil Nadu. The combined application of FYM, recommended fertilizer dose, and foliar application of 3% Panchagavya at 20 DAS resulted in the highest grain yield, reaching 1652.5 kg/ha [1].

6.3. Pest and Disease Management

Grassy weeds commonly found in foxtail millet fields include *Echinochloa colonum*, *Enbinochloa crusgulli, Dactyloctenium aegypticum, Elusine indica, Setaria glauca, Cynodon dactylon, Phragmites karka, Cyperus rotundus,* and *Sorgbum balepanse.* Additionally, broad-leaved weeds like *Celoria argentia, Commelina benghalensis, Phylanthus niruri, Solanum nigrum* and *Amaranthus viridis* are prevalent. Weed control strategies typically entail two to three hand weeding sessions using a hoe, along with POE application of 2, 4-D sodium salt (80%) at a rate of 1.0 kg ai./ha around 20–25 DAS. Moreover, PE spraying of Isoproturon at a rate of 1.0 kg a.i./ha proves effective in managing weeds. For line-sown crops, it is recommended to perform two inter-cultivations and one hand weeding, while broadcasted crops may require two hand weeding sessions [1,13,28].

Shoot fly damage is commonly found in foxtail millet from planting to 6 weeks after the crop emerges. Initially, it dries the central shoot, causing a dead heart appearance, and later leads to excessive tillering, affecting tillers as well. Affected tillers may have empty ear heads, appearing white. Peak infestation usually happens in late July or early August. To control shoot fly, plant early during the monsoon onset or in late July. Increase seed rate by 1.5 times to counter seedling loss. Use fishmeal traps and apply phorate in furrows at 8–10 kg/acre. Carbofuron 3G @ 1.5 kg ai/ha as soil treatment effectively reduces shoot fly. Quinolphos spray @ 2 mL/L concentration also works well in reducing infestation [13].

In Japan, Blast was first reported, and subsequently in India in 1919 from Madras province, is characterized by spindle-shaped spots on leaf lumina. These spots enlarge under conducive conditions, leading to a bleached appearance of leaf blades from tip to base, resulting in a blast of foxtail millet foliage. Control measures for blast include sprays of Saaf (0.2%), carbendazim 0.05%, or tricyclazole 0.05%, with the initial spray at 50% flowering, followed by a second spray after 10 days. Rust, prevalent in Maharashtra, Uttar Pradesh, Madhya Pradesh, Tamil Nadu, Karnataka, Andhra Pradesh, and Bihar, manifests as minute brown uredosori on leaf surfaces, forming elongated, brown lesions. These lesions may also appear on leaf sheaths, culms, and stems, potentially causing premature drying of leaves and reduced grain yield. These diseases pose significant threats to foxtail millet production and require timely and appropriate control measures [13].

6.4. Cropping Systems

Foxtail millet adapts well to various cropping systems, including relay cropping, sequence cropping, and intercropping. Intercropping with legumes like groundnut and pigeon pea or other crops like mustard and sunflower has been found beneficial, promoting resource utilization, soil health, and sustainability. Studies indicate that intercropping systems result in higher gross and net incomes, efficient resource use, and increased economic returns compared to sole cropping, highlighting the potential for diversified cropping systems in foxtail millet cultivation [1,3,13,28].

7. EFFECT OF DIFFERENT VARIETIES OF FOXTAIL MILLET ON GROWTH ATTRIBUTES

Brunda *et al.* [31] conducted a study at Agriculture Research Station Nipani and found that RFM 8 was the shortest variety (68 cm), while K 2 was the tallest (138 cm). Jyothi *et al.* [20] observed taller plants with SiA 3156 (93.7 cm) compared to SiA 3088 (79.9 cm). Srikanya *et al.* [32] reported significant differences in plant height due to sowing dates, with SiA 3156 being the tallest (120.4 cm). Deva *et al.* [33] found that SiA 3088 recorded higher plant height (114.4 cm) among several varieties. Nagaraja *et al.* [34] observed higher plant height with the GPUF 3 variety (118–142.3 cm) compared to SiA-3156.

Jyothi *et al.* [20] reported that the variety SiA 3156 and SiA 3085 (76) produced a higher number of tillers and a lower number for SiA 3088 (73). Nandini *et al.* [35] found SiA 2644 had a higher number of tillers $hill^{-1}$ (30.64) compared to other varieties. Deva *et al.* [33] observed that SiA 3088 recorded a higher number of tillers per $plant^{-1}$ (7.4) among several varieties. Srikanya *et al.* [32] noted variations in tiller numbers among varieties, with SiA 3085 having the highest number (93). Nagaraja *et al.* [34] found that SiA-3156 recorded a higher number of tillers (2.4–4.6) compared to GPUF 3.

Jyothi *et al.* [20] observed higher dry matter production with SiA 3085 and SiA 3156 (3153 and 3135 kg/ha, respectively). Srikanya *et al.* [32] reported maximum dry matter accumulation with SiA

3085 (354.1 g m^{-2}) among several varieties. These studies highlight the varying growth patterns and attributes influenced by different varieties of foxtail millet, emphasizing the importance of selecting appropriate varieties for optimal crop management and productivity. Understanding the growth patterns of different foxtail millet varieties is essential for effective crop management strategies. Farmers can select varieties based on desired traits such as plant height, tiller abundance and dry matter production, aligning with specific agroecological conditions and production goals.

8. EFFECT OF DIFFERENT VARIETIES OF FOXTAIL MILLET ON YIELD AND YIELD ATTRIBUTES

Researchers have extensively documented the variability in the number of productive tillers per plant across different foxtail millet varieties. Brunda *et al.* [31] highlighted significant differences in productive tiller counts among varieties across seasons. For example, in the rainy season, DHF 8, GS 592, and GS 2197 exhibited the highest number of productive tillers (15), while Krishnadevaraya and Ise 140 had the lowest (5). Similarly, in the summer season, Pratapkagni and K 222-1 displayed the highest number of productive tillers (41), whereas DHF 25 and GS 1483 recorded 16 tillers per plant. Nandini *et al.* [35] reported that SiA 2644 exhibited a higher number of productive tillers per hill (9.76), comparable to HMT-1 but significantly different from the local variety.

Test weight, reflecting grain density, showed variations among foxtail millet varieties as noted by researchers. Brunda *et al.* [31] reported RFM 10, SiA-3085 and Meera exhibited the lowest test weight (2.08 g), while GS 2159, Srilakshmi and DHF 2 displayed the highest (3.87 g). Kim and Yoon [36] found variations in thousand-grain weight among different varieties of foxtail millet and proso millet. Srikanya *et al.* [37] and Deva *et al.* [33] reported non-significant differences in test weight among varieties such as SiA 3085, SiA 3156, Suryanandhi and check varieties.

Regarding grain yield, significant differences were observed among foxtail millet varieties. Brunda *et al.* [31] reported significant differences in grain yield among varieties across seasons, with DHF 1 and DHF 26 exhibiting the highest yields in rainy and summer seasons, respectively. Jyothi *et al.* [20] found SiA 3085 to have the highest grain yield (1141 kg/ha), followed closely by SiA 3156, while SiA 3088 recorded the lowest yield (1001 kg/ha). Various other studies (Kim and Yoon [36], Ramyasri *et al.* [21], Nandini *et al.* [35], Deva *et al.* [33], Srikanya *et al.* [32,37], Nirmalakumari *et al.* [25], Nagaraja *et al.* [34]) have reported significant differences in grain yield among different varieties, highlighting the importance of varietal selection for maximizing yield potential.

Variations in straw yield among foxtail millet varieties have also been documented. Brunda *et al.* [31] observed significant differences in straw yield among varieties across seasons, with DHF 5 and Chithra exhibiting the highest yields in rainy and summer seasons, respectively. Similarly, Jyothi *et al.* [20] found SiA 3085 to have the highest straw yield (1956 kg/ha), followed closely by SiA 3156, while SiA 3088 recorded the lowest yield (1772 kg/ha). Other studies (Ramyasri *et al.* [21], Nandini *et al.* [35], Srikanya *et al.* [32,37], Nirmalakumari *et al.* [25], Nagaraja *et al.* [34]) have reported significant differences in straw yield among different varieties.

Harvest index, reflecting the proportion of grain yield to total biomass, exhibited variations among foxtail millet varieties. Jyothi *et al.* [20] observed differences in harvest index among varieties, with SiA 3088 exhibiting the highest index (37.9%), followed by Srilakshmi and SiA 3085, while SiA 3156 had the lowest (35.8%). Nandini *et al.* (2019) reported similar harvest indices for SiA 2644, HMT-1, and the local variety. Srikanya *et al.* [32] found non-significant differences in harvest index among varieties, with SiA 3085 showing a numerically higher index compared to SiA 3156 and Suryanandhi.

These findings emphasize the importance of selecting appropriate varieties based on yield attributes for maximizing overall productivity in foxtail millet cultivation. By understanding the yield potential and attributes of different foxtail millet varieties and implementing appropriate management strategies, farmers can optimize production and contribute to food security and livelihood improvement.

9. EFFECT OF DIFFERENT VARIETIES OF FOXTAIL MILLET ON QUALITY PARAMETERS

Nandini *et al.* [35] observed that SiA 2644 exhibited the highest protein and fiber content at 8.84% and 5.54%, respectively, which was comparable to HMT-1 with 8.18% protein and 5.70% fiber. Conversely, the local variety showed the lowest levels at 7.86% protein and 5.47 % fiber. Similarly, Nirmalakumari *et al.* [25] found that ATL-1 had the highest protein, mineral matter, calcium, and iron content at 12.3%, 3.5%, 34 mg/100 g, and 5.7 mg/100 g, respectively, surpassing CO (Te) 7 and other check varieties. Conversely, CO (Te) 7 exhibited the highest carbohydrate, fat and crude fiber content at 62.6%, 4.7%, and 8.4%, respectively, compared to ATL-1. In a recent study by Nagaraja *et al.* [34], it was found that the new variety GPUF 3 had higher calcium content at 108.6 ppm compared to the check variety SiA-3156 at 93.9 ppm. Conversely, SiA-3156 exhibited higher iron, zinc content, and protein percentage at 51 ppm, 65.5 ppm, and 13.8%, respectively, compared to GPUF 3 in their multi-location trials on new high-yielding foxtail millet varieties.

These findings underscore the significance of foxtail millet varieties in influencing various quality traits such as protein, fiber, mineral content, and micronutrients. Understanding the impact of different varieties on end-use quality is crucial for meeting consumer preferences and aligning with market demands, ultimately enhancing the overall value and utilization of foxtail millet in diverse food products and formulations.

10. EFFECT OF DIFFERENT VARIETIES OF FOXTAIL MILLET ON NUTRIENT UPTAKE

Studies by Jyothi *et al.* [20] and Ramyasri *et al.* [21] shed light on the impact of different foxtail millet varieties on nutrient uptake. In their investigation at S.V. Agriculture College Farm in Tirupati, Jyothi *et al.* [20] found notable disparities in nitrogen uptake among three evaluated varieties during the Kharif season. SiA 3085 and SiA 3156 exhibited similar nitrogen uptake levels, with values of 31.5 kg/ha and 30.7 kg/ha, respectively. Conversely, SiA-3088 displayed the lowest nitrogen uptake at 25.9 kg/ha. Ramyasri *et al.* [21] further emphasized the varietal differences in nitrogen uptake, with SiA-3156 recording the highest nitrogen uptake by grain (21.7 kg/ha) and straw (21.9 kg/ha) compared to SiA-3085 and SiA-3088.

Similarly, regarding phosphorous uptake, Jyothi *et al.* [20] reported that SiA 3085 exhibited the highest uptake at 16.6 kg/ha, followed by SiA 3156 at 15.7 kg/ha, while SiA-3088 had the lowest uptake at 13.7 kg/ha. Additionally, in terms of potassium uptake, SiA 3085 and SiA 3156 demonstrated comparable uptake levels, with values of 48.2 kg/ha and 46.2 kg/ha respectively, whereas SiA-3088 exhibited the lowest uptake at 44.9 kg/ha.

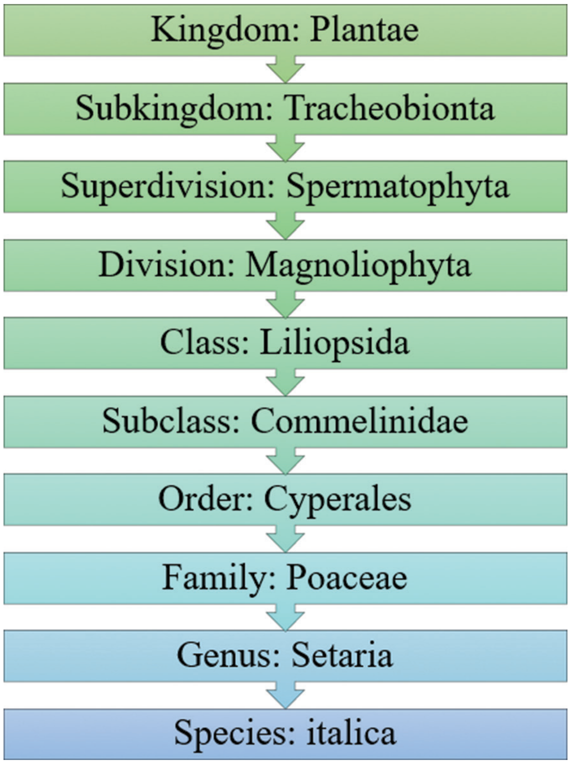

Figure 1: Taxonomy hierarchy of foxtail millet.

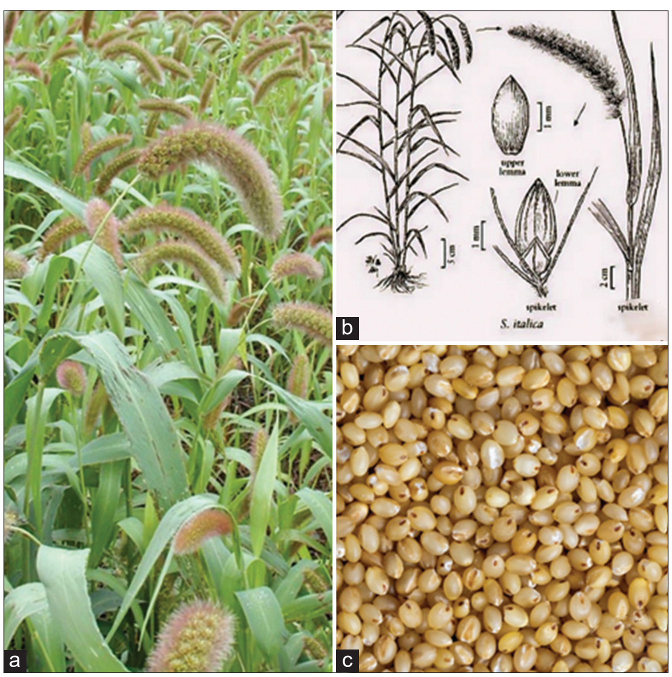

Figure 2: (a) Foxtail millet plants with inflorescence. (b) Anatomical description of foxtail millet. (c) Foxtail millet grain.

These findings underscore the varietal differences in nutrient uptake efficiency. Based on variety selection, Farmers can leverage this knowledge to optimize fertilizer application practices and improve crop nutrition, ultimately enhancing both crop yields and soil health. By selecting varieties with superior nutrient uptake capabilities, farmers can maximize nutrient utilization efficiency, reduce fertilizer waste and promote sustainable agricultural practices.

State	Varieties
Andhra Pradesh and Telangana	Renadu (SiA 3223), Garuda (SiA 3222), SiA 3088, SiA 3156, SiA 3085, Lepakshi, SiA 326, Narasimharaya, Krishnadevaraya, PS 4
Karnataka	HN 46, DHFt-109-3, HMT 100-1, SiA 3156, SiA 3088, SiA 3085, SiA 326, PS 4, Narasimharaya
Tamil Nadu	ATL 1, CO (Ten) 7, TNAU 43, TNAU-186, TNAU 196, CO 1, CO 2, CO 4, CO 5, K2, K3, SiA 3088, SiA 3156, SiA 3085, PS 4
Rajasthan	Prathap Kangani-1 (SR 51), SR 11, SR 16 (Meera), SiA 3085, SiA 3156, PS 4
Uttar Pradesh	PRK 1, PS 4, SiA 3088, SiA 3085, Sreelaxmi, Narasimharaya, SiA 326, S-114
Uttarakhand	PS 4, PRK 1, Sreelaxmi, SiA 326, SiA 3156, SiA 3085
Bihar	RAU-2, SiA 3088, SiA 3156, SiA 3085, PS 4

Figure 3: Improved foxtail millet varieties [22].

Nutrient	Foxtail Millet	Wheat (Whole)	Rice (Raw, Milled)
Carbohydrates (g)	60.9	71.2	78.2
Protein (g)	12.3	11.8	6.8
Fat (g)	4.3	1.5	0.5
Energy (Kcal)	331	346	345
Crude Fiber (g)	8	1.2	0.2
Mineral Matter (g)	3.3	1.5	0.6
Amylose (%)	17.5	25	12-19
Amylopectin (%)	82.5	75	88-81
Ca (mg)	31	41	10
P (mg)	290	306	160
Fe (mg)	2.8	5.3	0.7
Zn (mg)	2.4	2.7	1.4
Mg (mg)	81	138	90
Na (mg)	4.6	17.1	-
K (mg)	250	284	-
Cu (mg)	1.4	0.68	0.14

Figure 4: Foxtail millet versus fine cereals (per 100 g) [22]

11. MARKET TRENDS AND ECONOMIC IMPORTANCE OF FOXTAIL MILLET

The global foxtail millet market is projected to grow at a Compound Annual Growth Rate (CAGR) of 4.5% from 2021 to 2032 [38], driven by rising consumer demand for gluten-free, high-fiber, and low-glycemic foods. This growth parallels trends observed in other climate-resilient and health-oriented grains such as quinoa, sorghum, and pearl millet.

Compared to quinoa, which has a global reputation as a “superfood” and enjoys premium pricing in developed markets, foxtail millet offers a more affordable alternative with similar nutritional benefits and better adaptability to marginal environments. While quinoa’s international market is saturated and geographically concentrated (e.g., South America and Europe), foxtail millet’s production and consumption are expanding rapidly in Asia and Africa due to local cultivation and policy support [39].

In comparison to sorghum and pearl millet, foxtail millet shows faster growth in the organic and health-food sectors, especially in urban Indian and international markets. Pearl millet remains dominant in arid zones due to its drought tolerance, but foxtail millet has a competitive edge in value-added processing due to its finer grain texture, lower cooking time, and broader culinary versatility. India and China are the leading producers, with India alone contributing over 70% of global output. Government schemes like the National Food Security Mission, Millet Mission, and the declaration of 2023 as the International Year of Millets by FAO have catalyzed investment in production, marketing, and value chain development. Tools such as Agmarknet, FAOSTAT, and APEDA reveal a steady rise in exports to countries like the USA, UAE, Germany, and the UK, especially in the form of health-based processed foods [40,41].

Economically, studies indicate that improved foxtail millet varieties such as SiA 3085 and SiA 3156 offer high benefit-cost ratios, particularly under low-input conditions [20,32,33,37]. Compared to wheat and rice, which are highly input-intensive and less resilient to climate stress, foxtail millet ensures better net returns per unit of water and nutrient used, making it a sustainable choice for smallholders. This comparative market analysis positions foxtail millet not only as a functional food grain but also as a viable commercial crop that bridges nutritional, economic, and environmental goals across global agricultural systems.

12. NUTRITIONAL COMPOSITION

Foxtail millet, often overlooked, emerges as a promising solution to address global food challenges due to its exceptional nutritional profile. It is is rich in dietary fiber, protein (11–13%), and essential minerals such as iron, magnesium, and phosphorus. Its low glycemic index makes it beneficial for diabetic patients. Being gluten-free, it is suitable for people with celiac disease. Its high fiber content promotes gut health by supporting beneficial gut microbiota.

The nutritional composition of foxtail millet per 100 g [Figure 4] includes 60.9 g carbohydrates, 12.3 g protein, and 4.3 g fat, providing 331 kcal per serving. It also has 8 g crude fiber and 3.3 g mineral matter. The amylose content is 17.5%, while amylopectin is 82.5%. Additionally, it includes 31 mg calcium, 290 mg phosphorus, 2.8 mg iron, 2.4 mg zinc, 81 mg magnesium, 4.6 mg sodium, 250 mg potassium and 1.4 mg copper. Compared to major millet, foxtail millet surpasses them in all nutritional aspects, offering higher protein content, essential amino acids and sulfur-containing amino acids such as methionine and cysteine [42].

Chen *et al.* [43] and Yang *et al.* [44] analyzed Chinese cultivars, revealing high protein and amylopectin content using NIR spectroscopy. These findings corroborate Indian data while illustrating global consistency in nutritional superiority of foxtail millet." [42].

13. POSTHARVEST HANDLING OF FOXTAIL MILLET

Post-harvest handling of foxtail millet conventionally involves manual operations such as threshing with sticks, sun drying, and winnowing using baskets. While these practices are cost-effective and widely used in smallholder systems, they often lead to inconsistent drying, higher grain breakage, and contamination risks [45,46].

In comparison, mechanized threshing and controlled drying systems used in parts of China and Africa reduce labor dependency and improve grain quality by minimizing losses and ensuring uniform moisture content. For instance, the use of axial-flow threshers and mechanical dryers has shown to reduce post-harvest losses by up to 30% compared to traditional methods. Storage practices also vary: traditional granaries or underground pits may allow storage for 4–5 years, but they are susceptible to pest infestation and moisture variation. In contrast, hermetic storage technologies like PICS (Purdue Improved Crop Storage) bags or metallic silos offer better protection and longer shelf life.

A shift toward semi-mechanized and hygienic post-harvest systems, supported by policy and extension services, is essential to improve quality standards, meet export requirements, and promote value addition in foxtail millet value chains [45,46].

14. PROCESSING OF FOXTAIL MILLET

Processing methods for value addition in millets include various techniques to make them suitable for consumption and enhance their nutritional value and shelf life.

14.1. Dehulling/Decortication

Conventionally, millets were dehulled by hand pounding, but modern methods involve milling in rice milling machinery. Decortication improves consumer acceptability and nutrient availability by removing the tough outer coat of millets (Hulse *et al.* [47], Saleh *et al.* [48], Birania *et al.* [49]).

14.2. Milling

Millet grains undergo milling to remove the bran, seed coat, and other outer layers, resulting in products like flour and semolina. The use of abrasive milling machinery may not be effective for certain millet varieties, requiring alternative methods (Kurien and Desikachar [29], Kumar *et al.* [50], Birania *et al.* [49]).

14.3. Parboiling

Parboiling of millets improves their milling quality and reduces nutrient losses during processing, similar to rice (Desikachar [51], Shrestha [52], Birania *et al.* [49]).

14.4. Puffing/Popping

Puffing or popping millets creates ready-to-eat products with a crunchy texture and enhanced flavor. Optimal conditions for puffing include specific temperatures and moisture content (Malleshi and Desikachar [53], Ushakumari *et al.* [54], Birania *et al.* [49]).

14.5. Malting

Malting of millets, especially finger millet, enhances their flavor and nutritional value, making them suitable for beverages and infant food formulations. Malting also reduces antinutrients and improves digestibility (Seenappa [55], Desai *et al.* [56], Birania *et al.* [49]).

14.6. Extrusion

Extrusion technology transforms millet flours into value-added products like noodles and vermicelli. These products offer convenience and nutritional balance, catering to changing food habits (Birania *et al.* [49]).

14.7. Bakery Products

Millet flour is utilized in bakery products such as bread, biscuits, and muffins, providing micronutrients and fiber. Composite flours blending millets with other grains enhance acceptability and texture (Singh and Raghuvanshi [57], Eneche [58], Birania *et al.* [49]). Foxtail millet is increasingly used in health-based ready-to-eat products such as breakfast cereals, energy bars, noodles, snacks, cookies, and fermented foods. These products cater to urban health-conscious consumers. Compared to rice and wheat, foxtail millet has higher fiber, protein, and mineral content, making it a superior dietary choice in combating malnutrition.

15. HEALTH BENEFITS AND CULINARY USE

Foxtail millet plays a crucial role in promoting human health. It serves as an abundant source of fiber, protein, zinc, and magnesium, offering a well-rounded dietary profile [22]. With a moderate GI of 59, foxtail millet facilitates a gradual release of sugar into the bloodstream, contrasting with the rapid spikes associated with wheat and rice consumption [22]. The fiber content, primarily composed of β-glucans (42.6%), promotes enhanced metabolism of sugar and cholesterol, thereby reducing the risk of diabetes and cardiovascular diseases. It is often incorporated into low GI foods tailored for managing conditions like type 2 diabetes and cardiovascular ailments [22].

Moreover, the consumption of foxtail millet has been linked to various health benefits, including weight management, improved fasting blood sugar levels, enhanced blood pressure regulation, and a favorable lipid profile [22]. Its high fiber content contributes to improved digestion, alleviation of constipation, and a reduced risk of heart disease, hypertension, and stroke [22].

Beyond its nutritional content, foxtail millet is rich in essential B vitamins such as thiamin (B1), riboflavin (B2), niacin (B3), and folate (B9), which play vital roles in supporting nervous system and brain function [22]. In addition, its antioxidant properties, particularly attributed to flavonoids, aid in protecting neurons from inflammation, potentially enhancing memory function [22].

In culinary terms, foxtail millet offers versatility, being adaptable to various traditional and modern culinary applications. It can be utilized in a myriad of dishes, including porridge, bread, pudding, cakes, noodles, and more. Its use extends to the preparation of vinegar, wine, and beer in different culinary traditions worldwide. With its nutritional richness and culinary flexibility, foxtail millet holds significant potential in promoting human health and contributing to diverse and flavorful culinary experiences.

16. CONCLUSION AND FUTURE DIRECTIONS

Foxtail millet presents a valuable opportunity for enhancing global food and nutritional security, sustainable agriculture, and economic resilience, particularly in the context of climate change. Its high protein, fiber, and essential micronutrient content support human health, aligning with UNSDG 2 (Zero Hunger) and UNSDG 3 (Good Health & Well-being). The crop's ability to thrive in arid conditions with minimal inputs enhances climate adaptation efforts, supporting UNSDG 13 (Climate Action) and UNSDG 12 (Responsible Consumption and Production). The crop's adaptability to marginal environments and low-input conditions underscores its role in climate-smart farming systems. To fully realize its potential, strategic efforts are needed to promote suitable variety selection, improve agronomic practices, and strengthen value chains through consumer awareness and market access.

However, significant research gaps remain. Future work should focus on developing climate-resilient, high-yielding, and nutritionally enriched varieties through both conventional breeding and modern biotechnological approaches. Targeted studies are also needed to assess genotype performance across diverse agro-climatic zones and cropping systems. Strengthening research in post-harvest processing, value addition, and market development will further elevate foxtail millet's role in sustainable food systems. Multidisciplinary collaboration among researchers, policymakers, and stakeholders is essential to drive innovation, adoption, and long-term impact.

17. AUTHORS' CONTRIBUTIONS

All authors made substantial contributions to the conception and design, acquisition of data, or analysis and interpretation of data; took part in drafting the article or revising it critically for important intellectual content; agreed to submit to the current journal; gave final approval of the version to be published; and agreed to be accountable for all aspects of the work. All the authors are eligible to be an author as per the International Committee of Medical Journal Editors (ICMJE) requirements/guidelines.

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This study does not involve experiments on animals or human subjects.

21. DATA AVAILABILITY

All the data is available with the authors and shall be provided upon request.

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23. USE OF ARTIFICIAL INTELLIGENCE (AI)-ASSISTED TECHNOLOGY

The authors declares that they have not used artificial intelligence (AI)-tools for writing and editing of the manuscript, and no images were manipulated using AI.

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