Turkish Journal of Agriculture - Food Science and Technology, 13(2): 529-538, 2025
DOI: https://doi.org/10.24925/turjaf.v13i2.529-538.7273

Turkish Journal of Agriculture - Food Science and Technology

Available online, ISSN: 2148-127X | www.agrifoodscience.com | Turkish Science and Technology Publishing (TURSTEP)

Integrating Millets into Modern Agriculture: A Strategic Pathway to Advancing Sustainability, Climate Resilience, and Nutritional Security

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A R T I C L E I N F O

Review Article

Received : 28.10.2024
Accepted : 26.11.2024

Keywords:
Drought
High temperature
Food security
Hidden hunger
Climate-smart agriculture

A B S T R A C T

Millets, including pearl millet, foxtail millet, and finger millet, among others, offer a complementary solution to traditional staple crops such as wheat, rice and maize, particularly in the context of climate change. Known for their resilience to heat, drought, and poor soil conditions, millets can be integrated into existing agricultural systems to enhance food security and nutritional diversity in regions increasingly affected by climate change. While millets may not replace staple crops, their cultivation alongside these staples provide several benefits, including improved nutritional outcomes and reduced environmental impact. Pearl millet, for instance, is rich in iron and zinc, addressing micronutrient deficiencies that are common in many developing regions. Finger millet's high calcium content makes it a valuable addition to diets in areas with limited access to dairy. These grains thrive in marginal environments, contributing to more sustainable farming practices with a lower environmental footprint. Incorporating millets into agricultural systems can reduce dependency on water-intensive crops, lower the risk of crop failure, and provide a buffer against the impacts of climate change. By diversifying cropping systems, millets could help to stabilize food production and improve nutritional outcomes without displacing the critical role of traditional staples in global diets. To maximize the benefits of millets, efforts should focus on improving value chains, supporting smallholder farmers, and increasing consumer awareness. Moreover, targeted research and supportive policies are critical to unlocking their full potential and integrating them effectively into global food systems. As the world faces the dual challenges of climate change and malnutrition, millets offer a viable pathway to enhance resilience and sustainability in agriculture, complementing staple crops and enriching global food systems.

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Introduction

Addressing hunger and ensuring food security for the growing global population are two of the most critical challenges of the globe nowadays (Altaf et al., 2023). Several factors contribute to this issue, including shortages of both micro and macronutrients, imbalances between food supply and demand, and conflicts that disrupt food production in various regions across the globe (Saxena et al., 2018). Declining food production rates coupled with the need to feed more than 9 billion people by 2050, could leave 2 to 3 billion individuals facing hunger and nutritional insecurity (Wheeler & Von Braun, 2013; Godfray et al., 2010). Climate change, along with rising global temperatures, directly threatens agricultural productivity and the overall sustainability of food systems. While some regions may see productivity gains due to climate change, these increases will be insufficient to meet global food demand (Liaqat et al., 2022). Many scientists agree that current levels of global warming and greenhouse gases (GHG) emission will sharply reduce crop productivity. To secure a sustainable food supply, controlling global temperatures by controlling GHG emissions is unavoidable. However, the agricultural sector itself is a major source of emissions, particularly methane, due to intensive farming operations (Chataut et al., 2023).

Agriculture is often viewed as a cornerstone of national and food security due to its essential role in human survival. However, the growing challenges posed by climate change and an expanding global population are causing widespread concern (Muluneh, 2021). Both human-made and natural disasters continue to disrupt agricultural productivity and food systems, jeopardizing the ability to meet the rising demand for nutrition and energy (Mishra et al., 2021). Farmers now face the compounded difficulties of adapting to climate change alongside uncertainties in production, market fluctuations, transportation, and income stability (Rasul, 2021). These issues have a direct and/or indirect impact on agriculture and food systems, leading to socio-economic instability, especially among vulnerable populations. To address these pressing concerns, a shift is required from incremental adjustments to more transformative approaches that prioritize human health, nutrition, and environmental sustainability. This need is particularly urgent given the ongoing natural and man-made crises, emphasizing the importance of building a climate-resilient agricultural framework (Hossain et al., 2021). One promising approach is the integration of "orphan crops" into food systems which have the potential to diversify agricultural production while offering more nutritious food options (Talabi et al., 2022). Orphan crops are traditional crops that have been largely neglected in terms of scientific research, commercial development, and policy support, despite their significant potential to address nutritional and food security challenges, particularly in marginal environments (Mabhaudhi et al., 2019). Examples include millets, sorghum, and teff, among others, which thrive in diverse climatic conditions and offer high nutritional value. The rising interest in orphan crops is reflected in global efforts, such as the United Nations' designation of 2023 as the "International Year of Millets," aiming to promote their role in sustainable agriculture, climate resilience, and nutritional security.

Millets, among the oldest and most adaptable grains hold significant importance for ensuring food security, improving nutrition, and providing income for smallholder farmers in developing regions. Nevertheless, despite their historical significance, these grains have been largely neglected in recent years, with minimal scientific focus on enhancing their yields under stressful environmental circumstances (Kumar et al., 2018). As orphan crops, millets often outperform other crops in response to climate change, thanks to their unique characteristics such as thriving on marginal lands, requiring little water, and demonstrating resilience to both biotic and abiotic stresses (Kumar et al., 2023). The pressing challenges of climate change and pandemics call for swift and robust policies to safeguard food and nutritional security especially for communities already burdened by poverty (Bisoffi et al., 2021).

Millets play a critical role in addressing "hidden hunger," a term used to describe micronutrient deficiencies that affect billions of people globally, often without visible symptoms. Unlike macronutrient deficiencies, hidden hunger impairs immune function, cognitive development, and overall well-being (Srivastava and Arya, 2021). Millets are a powerhouse of micronutrients such as iron, zinc, calcium, and magnesium, which are essential for preventing diseases caused by deficiencies, such as anemia and osteoporosis (Kumar et al., 2024). For instance, pearl millet is rich in iron and zinc, addressing common deficiencies in developing regions, where anemia is widespread. Finger millet, known for its exceptionally high calcium content, is particularly beneficial for children and lactating mothers who require higher calcium intake (Anitha et al., 2021). Barnyard millet, with its high fiber content and low glycemic index, not only improves gut health but also supports better absorption of these micronutrients. Incorporating millets into regular diets can substantially alleviate hidden hunger by providing essential micronutrients in bioavailable forms (Mazumder et al., 2024). This is especially crucial in low- and middle-income countries, where diets often lack diversity and are predominantly composed of calorie-dense but nutrient-poor staples like rice and wheat.

This review focuses on how millets are important for a sustainable agricultural system. Furthermore, this review summarizes the unique properties of millets and their nutritional and health benefits. Additionally, we discuss strategies for integrating millets into mainstream agriculture through policy creation and research investment.

Global Cultivation and Production of Millets

Millets are grown across 93 countries globally (Meena et al., 2021). Figure 1 illustrates the global distribution of millet cultivation, highlighting the regions where different types of millets are predominantly grown. Africa emerges as a major hub for millet cultivation, particularly in semi-arid and arid zones, where these crops thrive under rainfed conditions. The figure underscores millet's role in ensuring food security in regions prone to drought and poor soil fertility. In Asia, millet cultivation is particularly significant in India and China, with these countries accounting for a substantial proportion of global production. The figure emphasizes millet's adaptability to diverse climates, making it an indispensable crop in global agricultural systems. This spatial representation underscores the importance of millet in combating climate challenges and supporting smallholder farmers. In China, millets have long been a dietary staple, particularly in the cold, arid northern regions where foxtail, proso, and barnyard millet varieties are most commonly grown. In Latin America, millet cultivation is concentrated in Mexico, primarily for animal feed while in North America, proso millet is mainly grown as bird feed in the Great Plains and Midwest (Kheya et al., 2023). Globally, the top millet producers are India, Nigeria, and China which collectively account for over 60% of the world's millet production (Table 1). India alone contributes 80% of Asia's millet output and 20% of global production. Although India has historically been the leading producer, recent years have seen a surge in millet cultivation in Africa. Globally, sorghum accounts for 65% of the total millet production (Amit Tomar et al., 2023).

Types of Millets

Pearl Millet (Pennisetum glaucum)

Pearl millet ranks as the world's sixth most significant cereal, predominantly cultivated across Central, Eastern, and Southern Africa, the Sahel region, Pakistan, and India. This resilient crop survives in arid environments and nutrient-poor sandy soils, tolerating minimal annual rainfall ranging from 200 to 500 mm (Prasad et al., 2020). It plays a critical role in ensuring food security, particularly in Africa and India (Nagaraj et al., 2013; Jukanti et al., 2016).

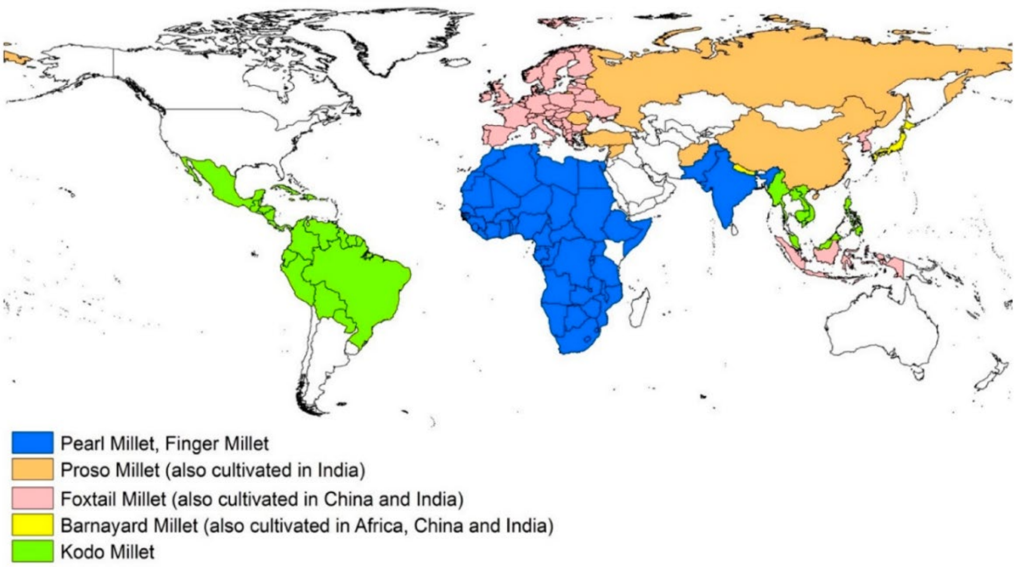

Figure 1. Cultivation of different types of millets around the world (Saxena et al., 2018).

Table 1. Top ten producing countries of millets in 2023 (USDA, 2024).

Country	% of global production	Total production (Metric Tons)
India	41%	12.2 million
Niger	11%	3.16 million
China	9%	2.7 million
Mali	7%	1.94 million
Nigeria	5%	1.56 million
Senegal	5%	1.35 million
Ethiopia	4%	1.1 million
Burkina Faso	3%	861,000
Sudan	2%	684,000
Chad	2%	634,000

Finger Millet (Eleusine coracana)

Finger millet is primarily cultivated across regions of India and Africa, ranking as the sixth most important cereal grain in India. Known for its resilience, it tolerates higher temperatures and soil salinity better than most cereal crops. Optimal growth occurs in temperatures ranging from 11 to 27°C, with a soil pH preference between 5 and 8.2 (Upadhyaya et al., 2008; Devi et al., 2014).

Proso Millet (Panicum miliaceum)

Proso millet, originally from Central and Eastern Asia, is now widely cultivated in areas such as India, Russia, the Middle East, and Europe. This crop thrives in short growing seasons, typically maturing within 60 to 75 days, and flourishes under minimal rainfall and moderate temperature conditions (Santra et al., 2019; Djanaguiraman et al., 2020).

Foxtail Millet (Setaria italica)

Foxtail millet is extensively grown across Europe, China, India, and other regions. It stands out for its rapid maturation, superior photosynthetic efficiency, and greater water-use efficiency compared to crops like maize and sorghum (Singh et al., 2017; Moharil et al., 2019).

Barnyard Millet (Echinochloa spp.)

Japanese barnyard millet (*Echinochloa utilis*) and Indian barnyard millet (*Echinochloa frumentacea*) are widely grown in countries such as India, China, Japan, and Nepal. Known for their drought resilience and quick maturation, these millets are also highly valued for their nutritional richness (Jayakodi et al., 2019; Mohanapriya et al., 2024).

Kodo Millet (Paspalum scrobiculatum)

The distribution of Kodo millet is extensive in moist environments throughout tropical and subtropical regions worldwide. This is an indigenous cereal originating from India. It contains a high protein level of 11%, as well as a low fat content of 4.2% and a very high fibre content of 14.3%. Easily digestible, Kodo millet is rich in lecithin and is highly beneficial for enhancing the functioning of the nervous system. Kodo millets are abundant in antioxidants, particularly niacin, B6, and folic acid, and with essential minerals like calcium, iron, potassium, magnesium, and zinc. Kodo millets are gluten-free and highly suitable for individuals with gluten intolerance (Dayakar Rao et al., 2017).

Little Millet (Panicum sumatrense)

This millet was domesticated in India. It is an annual herbaceous species that grows either straight or with folded blades to a height ranging from 30 cm to 1 m. It can withstand both drought and waterlogging. It is capable of being grown at elevations up to 2000 metres above sea level. Considering its early maturity and ability to withstand unfavorable agro-climatic conditions, it is another dependable catch crop. The stover is an excellent animal feed for cattle (Dayakar Rao et al., 2017).

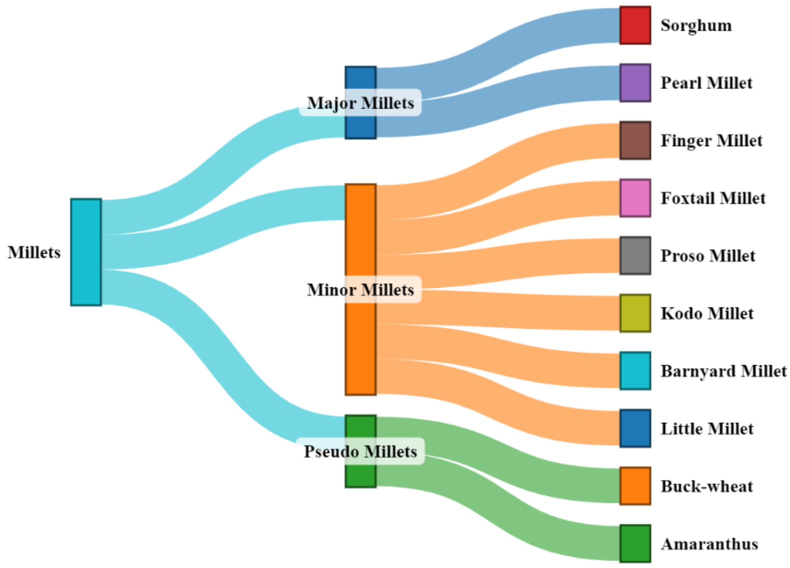

Figure 2. Types of millets.

Sorghum (Sorghum bicolor)

Sorghum is a highly adaptable and robust cereal crop primarily cultivated in the arid and semi-arid regions of Africa and Asia. Acknowledged for its exceptional drought resistance, sorghum is able to flourish in unfavorable soil conditions and endure high temperatures. It is also notably water-efficient compared to maize and wheat, which makes it an essential crop in water-scarce areas. Beyond its traditional use as food and animal feed, sorghum is gaining attention for its promising role in biofuel production (Liaqat et al., 2024; Liaqat et al., 2023). Figure 2 illustrates the classification of millets based on key characteristics, including seed size, plant type, and growth habits. Millets are broadly categorized into three groups: major millets, minor millets, and pseudo-millets (Amit Tomar et al., 2023).

Agronomic Advantages of Millets

Millets are exceptionally well-adapted to combat the adverse effects of drought and other abiotic stresses commonly encountered in semi-arid and arid regions. These stresses, which encompass drought, extreme temperatures, flooding, and salinity, adversely impact crop yields. Millets exhibit a variety of morpho-physiological, molecular, and biochemical characteristics that enhance their resilience to these environmental challenges (Chellapilla et al., 2022). For example, pearl and proso millet require only about 20 cm of rainfall, a stark contrast to rice, which demands 120 to140 cm (Kumar et al., 2018). Additionally, the relatively short growing period of millets (approximately 10 to 12 weeks) compared to major crops further aids in alleviating the impact of these stresses (Bandyopadhyay et al., 2017).

Millets possess a C4 photosynthetic pathway, a highly efficient mechanism that allows plants to thrive in high-temperature and low-moisture environments. This pathway enhances the concentration of carbon dioxide in the bundle sheath cells, significantly reducing photorespiration, a process that can waste energy and carbon. By improving water-use efficiency and carbon fixation, the C4 pathway enables millets to grow optimally under stressful environmental conditions where C3 crops, such as wheat and rice, may struggle. For instance, *Setaria italica* requires only 257 grams of water to produce one gram of dry biomass, compared to 470 grams for maize and 510 grams for wheat (Li & Brutnell, 2011; Nadeem et al., 2020). This heightened photosynthetic efficiency allows millets to grow better, allocate biomass more effectively, and maintain lower hydraulic conductivity in warm conditions.

Millets display several adaptive characteristics, including the ability to alter their flowering patterns in response to varying rainfall and to adjust membrane dynamics to maintain water balance during stress (Bidinger et al., 2007; Bandyopadhyay et al., 2017). In response to abiotic stresses, millets accumulate antioxidants and osmolytes, which further bolster their resilience (Ajithkumar & Panneerselvam, 2014; Tiwari et al., 2022). These features render millets an excellent model for investigating stress-responsive traits and mechanisms, essential for enhancing their adaptability and overall improvement.

Nutritional and health advantages of millets

Millets are integral to ensuring nutritional and health security, particularly in developing countries where vulnerable populations are disproportionately impacted by crises and pandemics. Enhancing the immune system is vital for protection against pathogens such as bacteria and viruses (Calder, 2020). Millets are distinguished by their high nutrient density (Table 2), which contributes significantly to their health benefits. In comparison to other major cereals, millets typically offer higher protein levels. For instance, finger millet contains between 11.64% to 13.6% protein (Onipe & Ramashia, 2022), foxtail millet ranges from approximately 11.13% to 18.75% (Sachdev et al. 2021), and proso millet provides 10.65% to 14.10% protein (Shen et al. 2018). Consequently, the substantial protein content of millets makes them a crucial source of plant-based protein in many dietary patterns.

Table 2. Nutritional value of millets and major cereals.

Crop	Protein (g/100 g)	Fibre (g/100 g)	Carbohydrate (g/100 g)	mg/100 g						
				K	Ca	P	Mg	Zn	Fe	Cu
Foxtail millet	12.3	8	60.9	299.3	38	422	81	2.9	5.3	1.6
Proso millet	12.5	7.2	70.4	177.3	23	281	117	2.4	4	5.8
Kodo millet	8.3	9	65.9	181.8	31	215	166	1.5	3.6	5.8
Finger millet	7.3	3.6	72	407	398	320	137	2.3	3.9	0.5
Barnyard millet	6.2	9.8	65.5	195	21	340	82	2.6	9.2	1.3
Pearl millet	11.8	2.3	67	275.7	46	379	137	3.1	8	1.1
Little millet	7.7	7.6	67	192.2	12	251	133	3.5	13.9	1.6
Sorghum	10.4	2	70.7	672	13.5	380	165	2.51	8.23	0.3
Wheat	6.8	1.2	71.2	107	34	357	137	2.6	3.6	0.4
Rice	11.8	0.2	78.2	35	21	433	177	6	2	0.2

Source: Muthamilarasan et al. (2016); Saleh et al. (2013); Choudhary et al. (2023)

Millets are abundant in both soluble and insoluble dietary fibers, which play a crucial role in regulating blood sugar levels and enhancing digestive health. Among these, pearl millet stands out as a particularly nutritious grain, offering superior levels of calories, protein, vitamins, and minerals compared to other major cereals. It also contains phenolic compounds with demonstrated antidiabetic properties, making them a viable ingredient for foods aimed at managing diabetes mellitus (Pei et al., 2022). Additionally, pearl millet provides various health benefits, including a reduced risk of cardiovascular diseases, diabetes mellitus, cancer, and decreased tumor incidence. It can also contribute to lower blood pressure and reduced cholesterol levels (Pei et al., 2022). Rich in B complex vitamins and high in antioxidants, millets support detoxification by eliminating harmful toxins and neutralizing free radicals, which may help prevent conditions such as heart diseases and cancer (Kumar et al., 2021).

Millets are a valuable source of essential nutrients, including calcium, iron, potassium, magnesium, phosphorus, manganese, zinc as well as important compounds such as vitamins, amino acids, and fatty acids (Muthamilarasan & Prasad, 2021). Finger millet stands out for its high levels of calcium, iron, and zinc, while pearl millet is especially rich in zinc and iron (Kumar et al., 2021; Kumar et al., 2022). Millets are also abundant in magnesium and potassium, which can help lower blood pressure by acting as vasodilators, thereby reducing the risk of cardiovascular diseases. Moreover, their high fiber and mineral content contributes to alleviating digestive issues such as constipation, bloating, excess gas, and cramping (Rodríguez et al., 2020). Similarly, millets offer a range of health benefits, including antioxidant, anticancer, anti-inflammatory, antifungal effects, and support for blood clot prevention.

Finger millet stands out among cereals for its exceptionally high calcium content, exceeding 0.3%, which makes it particularly advantageous for bone and dental health, especially for children (Ceasar et al., 2018; Antony Ceasar & Maharajan, 2022). In addition, its fiber and mineral levels surpass those found in rice and wheat (Gull et al., 2014). Moreover, finger millet is relatively rich in protein and provides a well-balanced amino acid profile, including lysine, threonine, and valine, which are frequently deficient in other starchy cereals (Anitha et al., 2020).

Barnyard millet, known for its high crude fiber content, supports better blood glucose regulation and has a lower glycemic index. In contrast, other types of millet, such as foxtail millet, are abundant in essential minerals and vitamins. Little millet is a good source of iron and fiber, while pearl millet is particularly high in protein. Including millet in the diet can help people in low and middle-income countries meet their nutritional needs, thereby contributing to sustainable development goals (Kumar et al., 2016; Goron & Raizada, 2015). Millets present a diverse range of micronutrients, addressing cereal needs while supporting long-term nutritional security. They also offer a viable substitute for wheat flour for those with celiac disease. Additionally, millets support sustainable agricultural practices and align with the United Nation's objective of ensuring healthy lives and promoting well-being for people of all ages.

Millets As Climate-Smart Crops

Millets offer a sustainable alternative in the context of climate change due to their resilience against the negative effects of global warming. As C4 plants, millets are adept at utilizing atmospheric CO_2 more effectively, converting it into biomass while emitting fewer GHG, with emissions ranging from 3218 to 3358 kg CO_2 equivalent per hectare (Jain et al., 2016). They exhibit notable climate-resilient traits, such as adaptability to diverse environmental conditions, reduced irrigation requirements, and enhanced growth with minimal nutrient inputs and environmental stress (Rajendrakumar, 2022). Millets are capable of thriving in higher temperatures and with less water, thus having a lower carbon footprint compared to other crops, which contributes to mitigating the global carbon impact (Bisht et al., 2022).

Millets offer several advantages due to their rapid life cycle and stress-adaptive traits. Their short stature, small leaf area, thicker cell walls, and deep root systems contribute to their resilience (Kencharaddi et al., 2024; Patan et al., 2024). The C4 photosynthetic pathway further reduces photorespiration and enhances efficiency under stress conditions. For instance, pearl millet thrives in poor sandy soils and adapts well to arid climates, while finger millet withstands salinity, high temperatures, and fluctuating soil pH (Kheya et al., 2023). Additionally, millets require substantially less water than crops such as rice and sugarcane, making them ideal for water-scarce regions. Their capacity to provide food, fodder, and income for smallholder farmers, combined with their potential for diverse products, underscores the importance of government support and further research in millet cultivation and market development.

Advances In Millet Research and Genomic Sequencing

Millets, traditionally cultivated in South Asia and Central Africa, have gained significant global research attention due to their exceptional nutritional benefits and adaptability to climate change. Twenty years ago, millet research was primarily limited to Asia, particularly India, and attracted minimal interest from high-income countries. Recently, however, this focus has broadened, with researchers from regions including Europe and America actively engaging in millet studies. This shift has led to an increase in published studies in reputable journals, reflecting the growing recognition of millets' potential.

Advancements in genomic sequencing have further driven millet research, enabling the identification of genes and traits linked to stress resilience and nutritional enrichment. Genomes of various millet species, such as foxtail millet (Setaria italica), finger millet (Eleusine coracana), pearl millet (Pennisetum glaucum), proso millet (Panicum miliaceum), and barnyard millet (Echinochloa spp.), have been sequenced, providing valuable insights (Zou et al., 2019; Hatakeyama et al., 2018; Hittalmani et al., 2017; Guo et al., 2017; Varshney et al., 2017; Bennetzen et al., 2012; Zhang et al., 2012). Foxtail millet was the first minor millet to have its genome fully sequenced, paving the way for understanding genes related to stress adaptation. The Phytozome database now includes a fully annotated genome for finger millet (https://phytozome-next.jgi.doe.gov/info/Ecoracana_v1_1), further advancing the study of its stress-resilient and nutrient-rich traits. However, many other millet genomes remain in draft form, lacking full annotation, which limits their utility for genetic studies.

The availability of genome sequences, whether annotated or in draft form, holds great promise for advancing research on millets' nutrient enrichment and climate resilience mechanisms. For instance, studying quantitative trait loci (QTL) associated with calcium levels in finger millet offers a pathway to address global calcium deficiencies (Antony Ceasar and Maharajan, 2022). While progress has been made in identifying genes and QTL for biotic and abiotic stress in major cereals like rice, wheat, and maize, similar studies in millets remain limited. Genome-editing tools, such as CRISPR/Cas systems, represent a promising avenue to enhance millet productivity and stress resilience. However, challenges in genetic transformation and regeneration techniques must be overcome to fully leverage these tools. Future research should prioritize complete genome annotation and the development of effective transformation protocols to accelerate millet improvement and ensure their role in global food security.

Strategic Approaches for Mainstreaming Millets In Agriculture

Addressing climate change and pandemics poses considerable challenges due to their unpredictable nature and the potential for severe nutritional and economic consequences. These crises underscore the necessity for robust risk governance strategies that incorporate scientific insights into policy decisions to effectively manage both human and natural disasters (Mishra et al., 2021; Priyadarshini & Abhilash, 2021). To fully realize the benefits of underutilized crops such as millets, a collaborative approach involving local, regional, and international stakeholders is crucial. Such efforts should be aligned with global sustainable development goals and encompass comprehensive engagement across the entire value chain i.e., from research and production to marketing and consumption (Babele et al., 2022). Effective policymaking is essential to bridge existing knowledge gaps and facilitate collaboration among various sectors, thereby promoting the integration of these crops into mainstream agriculture (Talabi et al., 2022). The growing recognition of millets for their climate resilience and health benefits highlights the need for increased research and development in this area. Policies should therefore shift focus towards supporting these underutilized crops rather than solely concentrating on major staples like maize, rice, and wheat.

Policy Development and Investment for Millet Crops

Developing markets for orphan crops like millets necessitates the implementation of supportive policies and an enabling environment, which can be achieved through collaborations among national, regional, and international organizations. Governments need to craft integrated policies that highlight the importance of millet crops, fostering public-private partnerships to bolster agricultural sustainability in developing areas. It is essential to promote the adoption of advanced agricultural technologies by farmers and end-users and to enhance extension services that bridge research with farming practices (Bisoffi et al., 2021; Borelli et al., 2020). In addition, policies should address land use, marketing, and credit systems to facilitate the growth and commercialization of millet crops. Increasing millet adoption requires educational and awareness initiatives that emphasize the nutritional, environmental, and economic advantages of millets, coupled with programs aimed at diversifying diets.

Addressing challenges in post-harvest processing and storage is vital for scaling up millet grain production (Babele et al., 2022). The development of crop-specific equipment and storage facilities is crucial to minimize waste and preserve grain quality. Implementing effective storage solutions and enhancing supply chains will aid farmers and stakeholders by reducing losses and ensuring food security during adverse events (Baldermann et al., 2016; Muthamilarasan and Prasad, 2021).

Providing subsidies for smallholder farmers to invest in millet-specific machinery and storage infrastructure can further reduce production costs and enhance competitiveness in markets. Additionally, forming cooperatives or producer groups can empower farmers to access larger markets, negotiate fair prices, and reduce logistical barriers.

Investing in research networks and focusing on invasive species research are essential for improving the agricultural and economic value of less-studied crops. Additionally, the collection and management of germplasm from these crops are critical for preserving genetic diversity and mitigating the effects of biotic and abiotic stresses on crop productivity (Ye and Fan, 2021). Building interdisciplinary collaborations and obtaining funding from both national and international sources will enhance research into gene functions and stress resistance mechanisms. Engaging with government and non-governmental organizations for participatory research can harness indigenous knowledge and bolster millet research efforts. To integrate millets into modern food systems effectively, governments and organizations must promote millet-based products through public procurement programs, school feeding schemes, and awareness campaigns that highlight their health and environmental benefits (Shanker, 2024; Satyavathi and Bhat, 2024). The United Nations General Assembly designated 2023 as the International Year of Millets to spotlight their significance in food security and health benefits. This global acknowledgment underscores the importance of increasing awareness about the nutritional and climate-resilient properties of millets.

Major Hurdles in Millet Research and Development

Millets have attracted growing attention in genomic and genetics studies in recent years. Nevertheless, high-resolution forward and reverse genetic studies, similar to those conducted on model plants, has not yet been utilized for millets. This limitation is largely attributed to the absence of comprehensive and annotated genome sequences for many millet species (Antony Ceasar and Maharajan, 2022). At present, annotated genome sequences are available only for foxtail millet and finger millet (https://phytozome-next.jgi.doe.gov/), as well as for green foxtail (*Setaria viridis*), a wild relative of foxtail millet (Lu, 2002). In contrast, other millets, such as pearl millet, proso millet, and barnyard millet, have only draft genome sequences that lack annotation (Zou et al., 2019; Varshney et al., 2017; Guo et al., 2017).

To make optimal use of excellent quality functional genomic investigations, particularly those utilizing the CRISPR/Cas system, it is essential to have access to fully annotated genome sequences. In order to precisely target genes and minimize off-target effects, these extensive sequences are essential (Ceasar, 2022). Nevertheless, a significant obstacle in progressing reverse genetic studies in millets is the lack of effective procedures for transformation and regeneration. This limitation hampers the application of gene-editing techniques like CRISPR in millets. In contrast to model plants such as Arabidopsis, which benefit from the straightforward floral dip transformation method due to their brief life cycle, millets encounter significant obstacles in this area (Antony Ceasar & Maharajan, 2022).

Conclusions and future outlooks

The future of millet research and integration into modern agriculture is promising yet requires targeted efforts to overcome existing challenges. Continued advancement in genomic research and genome editing technologies such as CRISPR will be be essential to enhance the nutritional quality and stress resilience of millet varieties. Additionally, interdisciplinary collaborations focused on improving post-harvest processing, storage, and market accessibility will further solidify millets as a sustainable solution for addressing global food security and nutritional challenges. Exploring millet-based dietary interventions in diverse regions could provide valuable insights into their role in alleviating micronutrient deficiencies and promoting health. The development of high-resolution genome sequences and effective transformation systems will facilitate deeper insights into their genetic makeup, enabling precise genetic improvements. Investments in research should focus on improving crop-specific technologies for planting, harvesting, and processing millets to boost their production and marketability.

Policy frameworks and market strategies must be developed to support the widespread adoption of millets. Governments and institutions should establish favorable policies and create partnerships to enhance the visibility and accessibility of millets. Public-private partnerships can play a significant role in bridging gaps between research and practical applications, promoting millet consumption through education and awareness campaigns, and supporting local farmers. Moreover, addressing post-harvest challenges is essential for the large-scale adoption of millets. Advancing genomic tools to accelerate the identification of stress-tolerant and nutrient-dense traits in millets can further support their integration into global food systems. Developing suitable storage technologies and optimizing supply chains will prevent significant losses and ensure the efficient distribution of millet products. The creation of robust markets and infrastructure will enhance the viability of millets as a staple crop, particularly in regions facing food security issues.

Declarations

This article was presented in III. International (XV. National) Field Crops Congress 19-21 September 2024 Tokat / Türkiye

Author Contribution

All authors participated in the and design and completion of the study. W.L. and M.T.A. collected the material and wrote the first draft. C.B. and F.S.B. supervised, reviewed and made corrections to the article. All authors have reviewed and approved the final version.

Conflict of Interest

The authors declare no conficts of interest.

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