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Millet's Role as a Climate Resilient Staple for Future Food Security: A Review

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Authors' contributions

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ABSTRACT

This review comprehensively examines the role of millets as a sustainable and resilient food source in the context of global climate change and escalating food security challenges. Millets, a group of small-seeded grasses traditionally grown in semi-arid regions of Africa and Asia, are re-emerging as crops of significance due to their remarkable adaptability to harsh environmental conditions and their rich nutritional profile. The review begins by outlining the various types of millets, including pearl, finger, and foxtail millet, and their geographic distribution, emphasizing their adaptability to diverse climatic conditions. It then delves into the nutritional aspects of millets, highlighting their high content of dietary fiber, vitamins, minerals, and essential amino acids, making them a potent solution to combat malnutrition and micronutrient deficiencies prevalent in many developing regions. A critical focus is placed on the climate resilience of millets. Their exceptional drought tolerance, ability to thrive in poor soil conditions, lower water, and nutrient requirements compared to staple crops like wheat and rice, and resistance to pests and diseases underscore millets' potential as sustainable crops in increasingly unpredictable climatic scenarios. This resilience not only promises to bolster food security but also contributes to sustainable agricultural practices. It explores the challenges and limitations in millet cultivation, processing, consumer acceptance, and market integration. It highlights the current gaps in millet-focused agricultural policies, the need for improved processing technologies, and strategies to enhance consumer appeal and marketability. Innovations in millet breeding for enhanced traits, advances in processing technologies, and the impact of biotechnology and climate-smart agricultural practices are examined. These technological and scientific advancements present opportunities for overcoming existing challenges and enhancing the role of millets in global food systems. Also presents case studies from various countries, particularly India, illustrating successful initiatives in millet cultivation, integration into national food policies, and community-led efforts. These examples offer valuable insights into practical approaches for promoting millets.

Keywords: Millets; sustainability; nutrition; climate-resilience; biodiversity; drought-tolerance.

1. INTRODUCTION

Millets, a group of highly variable small-seeded grasses, are widely grown around the world as cereal crops or grains for fodder and human food [1]. They are traditionally important in parts of Africa and Asia, especially in semi-arid tropics of these continents [2]. Millets include species like pearl millet (*Pennisetum glaucum*), finger millet (*Eleusine coracana*), and foxtail millet (*Setaria italica*), each possessing unique nutritional benefits. These grains are rich in dietary fiber, vitamins, minerals, and protein, often surpassing more common grains like rice and wheat in nutritional value [3]. Cultivation-wise, millets are lauded for their resilience; they thrive in less fertile soils and require little water, making them particularly suitable for arid regions [4]. Food security, defined as the state where all people have physical, social, and economic access to sufficient, safe, and nutritious food, faces significant threats under the changing climate [5]. The impact of climate change on agriculture and food systems is profound, particularly in terms of increased frequency and severity of extreme weather events, which jeopardize food production [6]. Major staples like wheat, rice, and maize are highly vulnerable to these changes, often experiencing reduced yields due to factors like water scarcity and temperature fluctuations [7]. This situation is exacerbated by the ongoing global challenges of population growth and urbanization, making the pursuit of sustainable and resilient food systems more urgent than ever [8]. Given the backdrop of climate change and its implications for food security, this review aims to explore the potential of millets as a climate-resilient staple crop. This includes examining their nutritional benefits, adaptability to harsh environmental conditions, and their role in sustainable agricultural practices. The review also seeks to address the challenges and limitations associated with millet cultivation and consumption, aiming to provide a comprehensive analysis that can inform policy decisions and agricultural practices. Through this, the review contributes to the broader discourse on sustainable food systems, offering insights and recommendations that are pertinent to various stakeholders including farmers, scientists, policymakers, and consumers.

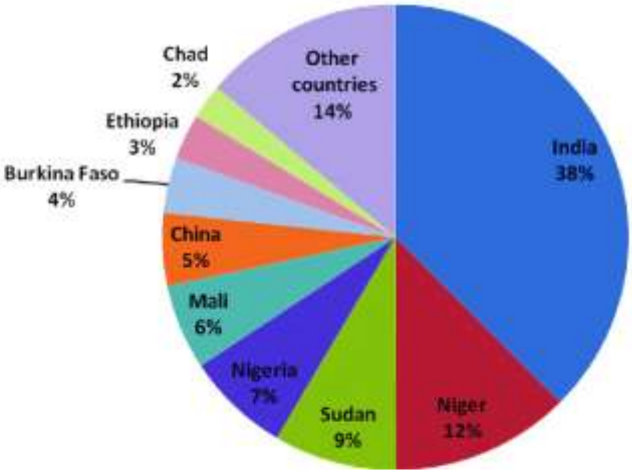

Image 1. Millet production (%) in different countries of the world [9]

Table 1. Millet Production, Market Dynamics, and Export Growth in India [10]

Category	Details
Total Millet Production (2021-22)	16 million tonnes
Percentage in National Food Grain Basket	5%
Major Types of Millets Produced	Pearl Millet: 9.62 million tonnes Jowar (Sorghum): 4.23 million tonnes Ragi (other significant millet)
India's Global Production Share (2020)	Pearl Millet: 40.51% Sorghum: 8.09%
Major Millet Producing States	Rajasthan, Karnataka, Maharashtra, Uttar Pradesh, Haryana, Gujarat, Madhya Pradesh, Tamil Nadu, Andhra Pradesh, Uttarakhand
Millet Market Growth Projection (2023-2028)	CAGR of 4.60%, from $11.02 billion to $13.80 billion
Millet Packaged Food Market Size (2022)	$39.5 million
Projected Market Growth (2023-2029)	CAGR of 10.2%, estimated to reach nearly $78.5 million
Export Growth (2021-22)	8.02%, with exports of 159,332.16 metric tonnes

2. MILLETS

Millets, a diverse group of small-seeded grasses, are traditionally important in semi-arid and arid regions of Africa and Asia. They are broadly classified into major and minor types, with major millets including the widely known pearl millet (*Pennisetum glaucum*) and finger millet (*Eleusine coracana*). Pearl millet is predominant in Africa and India, thriving in harsh environments with its exceptional drought resistance [11]. Finger millet, notable for its high calcium content, is a staple in East Africa and Southern India. Minor millets, such as foxtail millet (*Setaria italica*) and proso millet (*Panicum miliaceum*), have a more localized presence. Foxtail millet is common in East Asia, particularly in China, known for its short growing season and ability to thrive in marginal soils [12]. Proso millet has a global distribution, found in North America, Russia, and China, and can grow under a wide range of climatic conditions [13]. This geographical spread of millets underscores their versatility and adaptability to diverse climatic conditions.

2.1 Nutritional Profile of Millets

Millets are nutritionally rich, offering a high carbohydrate content and significant amounts of dietary fiber. They are a rich source of vitamins, particularly B-vitamins, and minerals such as iron, magnesium, and phosphorous. The health benefits associated with millets are notable; they have been recognized for their role in managing diabetes, cardiovascular diseases, and obesity. Importantly, millets are gluten-free, making them an excellent food choice for people with celiac disease or gluten intolerance [14]. In terms of phytochemicals, millets contain significant amounts of phenolic compounds, which contribute to their antioxidant properties [15]. The protein content in millets is comparable to that of wheat and maize, but with a higher proportion of essential amino acids. Finger millet, in particular, stands out for its high iron and zinc content, making it an important crop for addressing micronutrient deficiencies [16].

2.2 Historical Significance and Current Underutilization

Millets have been an integral part of human diets since prehistoric times, with archaeological evidence indicating their cultivation as far back as 7000 BC in China. They have historically been staple foods in parts of Africa and Asia, serving as a primary source of nutrition and playing a role in cultural practices and festivals [18]. Despite their historical significance and nutritional benefits, millets have been largely underutilized in recent decades, especially with the advent of the Green Revolution which focused heavily on high-yielding varieties of wheat and rice. This shift resulted in a decline in millet cultivation and consumption, overshadowing their nutritional and environmental benefits. However, recent initiatives have aimed to revive interest in millets, recognizing their potential in addressing food security, nutritional deficiencies, and their suitability in the context of climate change. Policies are gradually emerging to promote millet cultivation, backed by a growing awareness of their health benefits and environmental sustainability [19].

3. CLIMATE RESILIENCE OF MILLETS

Millets are exceptionally drought-tolerant, making them suitable for cultivation in arid and semi-arid regions where other cereal crops would fail. This tolerance is primarily due to their deep root systems, which enable them to access moisture from deeper soil layers. Pearl millet, for instance, is known for its remarkable drought tolerance, capable of producing reliable yields in areas with less than 400 mm annual rainfall [20]. Finger millet also exhibits substantial drought tolerance, with studies showing its ability to sustain grain filling even under moisture stress conditions [21]. The physiological mechanisms behind this tolerance include a higher rate of water-use efficiency and the ability to maintain cell turgor pressure under water deficit conditions [22]. Millets can thrive in nutrient-poor, less fertile soils where many other crops cannot sustain. This adaptability stems from their efficient nutrient use and ability to grow in low-fertility conditions. For example, pearl millet has a high affinity for phosphorus, one of the most limiting nutrients in tropical soils [23]. It can extract and utilize phosphorus more efficiently than many other cereals. Similarly, finger millet is known for its ability to grow in soils with high salinity or low pH, conditions that are typically challenging for agriculture [24]. The root architecture of millets, particularly their longer and denser root systems, contributes significantly to their ability to absorb nutrients in poor soil conditions. When compared to staple crops like wheat, rice, and maize, millets require significantly less water and nutrients. For instance, the water requirement for rice is about four times higher than that for millets [25]. This makes millets particularly important in regions where water scarcity is a major concern. Additionally, the nitrogen use efficiency of millets is higher than that of many cereals, which reduces the need for nitrogenous fertilizers. This not only makes millet cultivation more environmentally sustainable but also more economical for farmers in developing countries where access to agricultural inputs is limited [26]. Millets exhibit a higher resistance to pests and diseases compared to many other cereals. Their hardiness extends to a natural resilience against common pests and diseases that typically affect crops like maize and wheat. For instance, pearl millet has shown resistance to downy mildew, a disease that can significantly reduce yields in cereals [27]. The presence of certain bioactive compounds in millets acts as natural pest deterrents. This resistance is advantageous not only in reducing crop losses but also in minimizing the dependence on chemical pesticides, thereby promoting more sustainable agricultural practices [28].

Table 2. Nutritional composition of millets [17]

Nutrient	Pearl Millet	Finger Millet	Foxtail Millet	Proso Millet	Sorghum
Energy (kcal/100g)	361	328	351	354	339
Protein (g/100g)	10.6	7.3	11.2	12.5	10.4
Fat (g/100g)	4.8	1.5	4.0	3.0	3.3
Carbohydrates (g/100g)	67	72	63	70	75
Dietary Fiber (g/100g)	1.2	3.6	6.7	2.2	6.3
Iron (mg/100g)	8	3.9	2.8	0.8	4.4
Calcium (mg/100g)	42	344	31	8	28
Magnesium (mg/100g)	144	137	114	114	165
Phosphorus (mg/100g)	296	283	285	285	287
Potassium (mg/100g)	195	408	195	195	350
Zinc (mg/100g)	2.2	2.1	1.6	1.5	1.8
B-Vitamins	Present	Present	Present	Present	Present

Table 3. Climate Resilience Aspect

Climate Resilience Aspect	Description and Impact
Drought Tolerance	✓ Millets have a deep root system allowing them to access moisture in deeper soil layers. ✓ Can produce yields in low rainfall conditions.
Adaptability to Poor Soils	✓ Capable of growing in nutrient-poor, less fertile soils. ✓ Efficient nutrient use, especially in phosphorus-limited conditions.
Water Efficiency	✓ Require significantly less water compared to staples like rice and wheat. ✓ Suitable for dry regions and conditions of water scarcity.
Heat Tolerance	✓ Able to withstand higher temperatures, making them suitable for cultivation in areas experiencing rising temperatures.
Pest and Disease Resistance	✓ Natural resilience against many common pests and diseases. ✓ Reduces reliance on chemical pesticides, promoting sustainable practices.
Biodiversity and Variability	✓ Wide range of species with varying traits allows for cultivation in diverse climatic conditions. ✓ Contributes to agricultural resilience.

4. MILLETS AND FOOD SECURITY

Millets play a crucial role in ensuring nutritional security, especially in regions prone to food scarcity. Their rich nutritional profile, offering a balance of carbohydrates, proteins, dietary fiber, vitamins, and minerals, makes them an excellent food source for combating malnutrition [29]. For example, finger millet has a high calcium content, essential for bone health, while pearl millet is rich in iron and zinc, crucial for immune function and cognitive development [30]. Their inclusion in diets can help bridge the nutritional gaps often found in populations overly reliant on refined grains. Hidden hunger, or micronutrient deficiency, affects billions worldwide, especially in developing countries. Millets can be a solution to this problem due to their high content of essential micronutrients. Studies have highlighted the significant levels of iron, zinc, and B vitamins in millets, which are key to addressing deficiencies like anemia and beriberi [31]. Additionally, the bioavailability of these nutrients in millets is relatively high, meaning they can be effectively absorbed and used by the body. Integrating millets into diets can greatly enhance food diversity, which is crucial for balanced nutrition and food security. In many traditional diets, especially in parts of Africa and Asia, millets have been a staple for centuries, revered for their versatility and adaptability to local culinary practices [32]. The resurgence in millet consumption, driven by a growing awareness of their health benefits, is contributing to the revitalization of these traditional diets and the preservation of cultural food heritage. From an economic perspective, millets offer significant benefits. Their resilience to harsh growing conditions means they can be cultivated at a lower cost compared to more water and nutrientintensive crops like rice and wheat [33]. This cost-effectiveness is particularly important for smallholder farmers in developing countries. Moreover, the growing global health consciousness has opened up new markets for millets as health foods in both domestic and international markets. This presents an opportunity for economic growth, especially for communities traditionally engaged in millet cultivation [34].

5. CHALLENGES AND LIMITATIONS

One primary issue is the lack of improved seed varieties. While other major crops have benefited from extensive breeding programs, millets have received less attention, resulting in lower yields compared to crops like wheat and rice [35]. Additionally, millet farmers often face difficulties in accessing markets due to poor infrastructure and the small-scale nature of their operations. This issue is compounded by a lack of reliable and consistent demand, making it difficult for farmers to plan and invest in millet cultivation. Climate change poses a significant challenge. Although millets are drought-resistant, extreme weather patterns and unpredictable rainfall can still adversely affect yield and quality [36]. The situation is exacerbated by the limited knowledge and resources available to smallholder farmers for managing such risks. Processing and storage are critical aspects where millets face significant limitations. Traditional processing methods for millets are often labor-intensive and time-consuming, which can lead to inefficiencies and losses [37]. Moreover, the small size and hardness of millet grains require specialized processing equipment, which is not widely available, especially in rural areas where millets are primarily grown. In terms of storage, millets are susceptible to pest infestations and mold growth, particularly in humid conditions. Proper storage facilities are crucial to prevent post-harvest losses and maintain grain quality, but such facilities are often lacking in regions where millets are cultivated. This limitation not only affects the quantity but also the quality of the millet grains available to consumers. Consumer acceptance and cultural preferences significantly influence the demand for millets. In many regions, particularly urban areas, millets are perceived as 'poor man’s food' or as traditional grains that are not in line with modern eating habits [38]. This perception has led to a decline in millet consumption, especially among younger generations who often prefer more refined grains. The lack of awareness about the nutritional benefits of millets and limited availability of millet-based products in mainstream markets reduce their visibility and appeal to consumers. Changing dietary preferences and lifestyles have also contributed to the reduced consumption of millets. Policy and market barriers significantly impact the production, distribution, and consumption of millets. Government policies have traditionally favored staple crops like rice and wheat, often through subsidies and support programs, while neglecting minor cereals like millets [39]. This bias has limited investment in research and development for millet breeding, processing technologies, and market development. Market barriers also play a role. The fragmented nature of millet markets, with a predominance of small-scale producers and lack of organized supply chains, hinders the growth of a robust market for millets. Additionally, there is a lack of standardization in quality and pricing, which creates uncertainty and mistrust among consumers and traders alike. Addressing these policy and market challenges is crucial for the integration of millets into mainstream agricultural systems and food markets.

6. TECHNOLOGICAL AND SCIENTIFIC ADVANCES

The breeding of millets has seen significant advancements in recent years. Modern breeding techniques have focused on enhancing traits such as yield, nutritional quality, and resistance to pests and diseases. Hybrid varieties of pearl millet, for instance, have been developed, showing increased yield potential and better tolerance to environmental stresses [40]. Genetic engineering and marker-assisted selection are also being employed to introduce specific traits like drought tolerance and improved nutrient use efficiency into millet varieties. One of the key focuses of millet breeding is enhancing their nutritional profile. Biofortification, the process of increasing the nutrient content of crops through breeding, is being used to increase the levels of micronutrients like iron and zinc in millet grains. This approach holds significant promise for addressing micronutrient deficiencies in regions where millets are a dietary staple. The processing of millets has evolved considerably, moving from traditional, labor-intensive methods to more efficient, mechanized processes. Advances in milling technology have improved the recovery rate of millet grains, reducing wastage and increasing efficiency. The

Table 4. Technological and Scientific Advancements in Millet Cultivation and Processing [42]

Area of Advancement	Description of Advances
Genetic Breeding	✓ Development of hybrid and high-yield varieties. ✓ Use of genetic markers for trait selection. ✓ Biofortification to enhance nutritional content.
Disease and Pest Resistance	✓ Breeding for enhanced resistance to common pests and diseases. ✓ Utilization of biotechnology for developing pest-resistant strains.
Drought and Climate Resilience	✓ Genetic modification to enhance drought tolerance. ✓ Research on millet varieties best suited for changing climate conditions.
Agronomic Practices	✓ Improved cultivation techniques for higher efficiency. ✓ Climate-smart agricultural practices tailored for millet farming.
Processing Technologies	✓ Advanced milling and husking machines for better yield. ✓ Development of technologies for value-added products like millet-based snacks and beverages.
Post-harvest Handling	✓ Techniques for better storage and reduced post-harvest losses. ✓ Innovations in packaging to extend shelf life and maintain nutritional quality.
Nutritional Research	✓ Comprehensive studies on the health benefits of millets. ✓ Research on bioavailability and digestibility of nutrients in millets.
Biotechnological Applications	✓ Use of genome editing tools like CRISPR for trait improvement. ✓ Application of biotech for sustainable millet production.
Sustainable Farming Integration	✓ Integration of millets in sustainable farming systems like intercropping. ✓ Research on millets' role in enhancing soil health and biodiversity in agricultural ecosystems.
Market Development	✓ Efforts to standardize and improve millet grading and quality. ✓ Strategies to enhance market visibility and consumer acceptance of millet-based products.

development of decorticators, specific to millet grains, has made the process of husk removal more efficient, preserving the nutritional quality of the grains. In terms of value addition, there is a growing trend in developing millet-based products that cater to modern consumer preferences. These include ready-to-cook and ready-to-eat products, millet-based snacks, bakery items, and beverages. These innovations not only make millets more palatable and convenient for urban consumers but also increase their market value, providing an incentive for farmers to cultivate these crops. Biotechnology has played a crucial role in improving millet crops. Genetic modification and genome editing technologies like CRISPR/Cas9 are being explored to develop millet varieties with enhanced traits, such as improved resistance to pests and diseases and better adaptability to adverse climatic conditions [41]. This aspect of biotechnology is crucial for ensuring the sustainability of millet cultivation in the face of climate change. Alongside biotechnological advances, climate-smart agricultural practices are being implemented to enhance the resilience of millet farming systems. These practices include improved water management techniques, such as drip irrigation and rainwater harvesting, which are essential for millet cultivation in drought-prone areas. Additionally, the integration of millets into crop rotation and intercropping systems enhances soil health and biodiversity, contributing to the overall sustainability of agricultural practices.

7. CASE STUDIES

7.1 Success Stories of Millet Cultivation in Arid and Semi-Arid Regions (Indian Scenario)

Karnataka's Millet Model: Karnataka's initiative to promote millet cultivation amidst water scarcity. The state government's support through subsidies and training programs has been pivotal. Case of small-scale farmers in the semi-arid regions of Karnataka successfully adopting millet farming, improving both their resilience to climate change and economic stability [43].

Rajasthan's Bajra (Pearl Millet) Success: In Rajasthan, traditional farming practices have been revitalized with modern cultivation techniques for pearl millet. The involvement of agricultural universities and local government in aiding farmers with better seeds and farming practices [44].

7.2 Integration of Millets in National Food Security Policies: Examples from Various Countries

India's Poshan Abhiyan: India's flagship program, Poshan Abhiyan (Nutrition Mission), integrating millets to combat malnutrition. Policies supporting millet cultivation and inclusion in mid-day meal schemes in schools to improve children's nutritional intake [45].

Millets in Public Distribution System: The Indian government's recent moves to include millets in the Public Distribution System (PDS), recognizing their nutritional value and the need to support millet farmers [46].

7.3 Community-led Initiatives and Their Impact

Odisha's Millet Mission: The Odisha Millet Mission, a pioneering initiative by the state government, NGOs, and farmer groups to promote millet cultivation. The mission's holistic approach, from production to marketing, and its significant impact on smallholder farmers' livelihoods and local food security [47].

Women-led Millet Cooperatives in Tamil Nadu: In Tamil Nadu, women-led cooperatives have been instrumental in reviving millet-based traditional foods. These cooperatives have not only empowered rural women but also played a key role in sustaining the millet value chain, from cultivation to the consumer market [48].

8. FUTURE PERSPECTIVES

8.1 Potential Role of Millets in Sustainable Agriculture

Millets, with their low water and nutrient requirements, play a crucial role in sustainable agriculture, particularly in the face of climate change. Their ability to grow in harsh environmental conditions makes them an ideal crop for ensuring food security in areas prone to drought and poor soil quality [49]. In India, where a significant portion of agriculture is rainfed, millets offer a sustainable alternative to more water-intensive crops like rice and wheat. Additionally, some of millets have their deep root systems help in improving soil health and preventing erosion, contributing to the sustainability of the agricultural ecosystem. The biodiversity of millet species also contributes to agricultural sustainability. Unlike the monoculture of major cereals, millets offer a range of species that can be cultivated across different environments. This biodiversity is key to resilience against pests, diseases, and changing climate conditions [50]. Millets fit well into various cropping systems, including intercropping and crop rotation, enhancing soil fertility and reducing the need for chemical fertilizers.

8.2 Strategies for Promoting Millets in Global Food Systems

To boost the presence of millets in worldwide food systems, a variety of tactics can be implemented. A key step is to enhance public knowledge about the health advantages of millets. This objective can be reached by initiating public health initiatives, incorporating millets into school food programs, and partnering with culinary experts and food influencers to make dishes based on millets more popular. Policy support is essential for the integration of millets into global food systems [51]. This includes support for millet research, subsidies for farmers growing millets, and inclusion of millets in public food distribution systems. In India, policies like the inclusion of millets in the Public Distribution System (PDS) and initiatives like the Millet Mission of Odisha serve as examples of how government action can boost millet cultivation and consumption. Developing global markets for millets is another key strategy. This involves standardizing millet grading and quality norms, establishing millet processing units, and creating brands around millet-based products. International collaborations can help in sharing best practices and technologies for millet cultivation and processing [52].

8.3 Recommendations for Research, Policy, and Practice

1. **Research:** There is a need for more research on millet genetics, breeding for improved varieties, and sustainable

farming practices specific to millets. Research on millet-based food products, their health benefits, and ways to enhance their taste and acceptability is also crucial.

2. **Policy:** Policies should focus on supporting millet farmers through subsidies, insurance, and access to markets. Encouraging the use of millets in government-run programs like mid-day meals in schools can also boost demand. Policies should aim at integrating millets into national and international agricultural and nutritional strategies.
3. **Practice:** On the ground, practices like farmer training programs, demonstration plots, and farmer field schools can be effective in promoting the cultivation of millets. Encouraging the participation of women and youth in millet cultivation and business ventures can also be beneficial.

9. CONCLUSION

Millets emerge as a pivotal crop in addressing the challenges of sustainable agriculture and global food security, particularly in the context of climate change. Their inherent resilience to harsh environmental conditions, low water and nutrient requirements, and nutritional richness position millets as a viable solution for regions grappling with resource constraints and nutritional deficiencies. However, realizing their full potential necessitates concerted efforts in research, policy-making, and market development. Embracing millets in agricultural systems and food chains can significantly contribute to biodiversity, ecological sustainability, and dietary diversity. Future strategies should focus on enhancing millet varieties through scientific breeding, improving processing techniques, fostering policy support, and raising global awareness about their benefits. Integrating millets into our food systems is not just a step towards agricultural resilience but a stride towards a more sustainable and food-secure future.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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