Review Article

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Millets as Strategic Crops for Climate Adaptation, Resource Conservation and Sustainable Food Systems

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Abstract

Climate change is creating increasing challenges for agricultural production through rising temperatures, recurrent drought, irregular rainfall, soil degradation and increasing competition for water and other natural resources. These challenges are particularly severe in rainfed and semi-arid production environments, where crop productivity is strongly dependent on seasonal rainfall. Diversification with crops adapted to environmental stress is therefore an important strategy for strengthening agricultural resilience. Millets comprise a diverse group of cereal crops with considerable potential for climate-resilient and sustainable agriculture. Their adaptation to high temperature and water-limited environments, relatively short growth duration, efficient resource utilization and nutritional value make them suitable components of diversified farming systems. Most cultivated millets utilize the C4 photosynthetic pathway, while several species possess root and phenological characteristics that support productivity under drought and heat stress. In addition to their agronomic importance, millets provide carbohydrates, proteins, dietary fibre, minerals and bioactive compounds and can contribute to nutrition-sensitive agriculture. Their integration into crop rotations, intercropping systems and crop–livestock systems can distribute climatic risk and improve resource utilization. Advances in genomics, molecular breeding, high-throughput phenotyping and genome editing provide additional opportunities to improve drought tolerance, heat tolerance, yield stability and nutritional quality. However, inadequate seed systems, limited mechanization, processing difficulties, weak market linkages and insufficient consumer awareness continue to constrain millet expansion. This review discusses the physiological basis of millet climate resilience, their contribution to resource conservation and diversified farming, nutritional importance, genetic improvement, processing and value addition, major constraints and future research priorities. A systems-based approach integrating crop improvement, agronomy, processing, markets and supportive policy is required to convert the inherent resilience of millets into sustainable benefits for farmers, consumers and the environment.

Keywords: *millets; climate-resilient agriculture; drought tolerance; heat tolerance; C4 crops; crop diversification; resource-use efficiency; nutrition security; genomics; sustainable agriculture.*

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1. Introduction

Agriculture is increasingly exposed to environmental and socioeconomic pressures associated with climate change. Rising temperatures, changes in rainfall distribution, recurrent droughts and degradation of soil and water resources threaten agricultural productivity, particularly in rainfed regions. At the same time, dependence on a limited number of major cereal crops can increase the vulnerability of food systems to climatic shocks. Crop diversification is therefore an important component of climate adaptation. Diversifying agricultural production with crops possessing different physiological characteristics can reduce production risk and improve resilience. Millets are particularly relevant because many species were domesticated and selected in semi-arid regions where adaptation to environmental stress was an important component of crop evolution [1]. Millets comprise several cereal species, including pearl millet, finger millet, foxtail millet, little millet, kodo millet, barnyard millet and proso millet. These crops have traditionally contributed to food security in parts of Africa and Asia, especially in environments where water availability is limited.

The physiological characteristics of millets are particularly relevant to climate adaptation. Their C4 photosynthetic pathway, adaptation to high temperatures, drought tolerance, relatively short growth duration and capacity to perform under low-input conditions provide a foundation for their use in climate-resilient farming systems [1,2]. Pearl millet is particularly important in this context. It possesses a deep root system, high photosynthetic efficiency and adaptation to water-limited and low-fertility environments [8]. Its ability to maintain productivity under harsh environmental conditions has resulted in increasing interest in its use as a climate-resilient crop. The nutritional characteristics of millets further strengthen their importance. Millet grains provide carbohydrates, proteins, minerals, dietary fibre and bioactive compounds, while species and genotypes differ substantially in nutritional composition [3,4]. Pearl millet, for example, can provide important amounts of iron and zinc, making it relevant to nutrition security [8].

This review therefore examines the potential of millets as strategic crops for climate adaptation, sustainable resource management, crop diversification and nutrition security.

2. Diversity and Agricultural Importance of Millets

Millets represent a taxonomically diverse group of cereals with different environmental adaptations and uses. Pearl millet (*Pennisetum glaucum*; *Cenchrus americanus*) is widely cultivated in the arid and semi-arid regions of Africa and South Asia. Finger millet (*Eleusine coracana*) is important in eastern Africa and South Asia, whereas foxtail millet (*Setaria italica*), little millet (*Panicum sumatrense*), kodo millet (*Paspalum scrobiculatum*), barnyard millet (*Echinochloa* spp.) and proso millet (*Panicum miliaceum*) contribute to diversified agricultural systems. The diversity of millet species is valuable from a climate adaptation perspective because different species and genotypes can be matched to specific environmental conditions. Rather than promoting millets as a single crop category, climate-smart agricultural programmes should exploit their species-level and genotype-level diversity. Pearl millet has received considerable research attention because of its importance in hot and dry environments. The crop is grown extensively in regions where rainfall is low and variable and where high temperatures restrict the productivity of several other cereals [2,8].

3. Physiological Basis of Millet Climate Resilience

3.1 C4 photosynthesis

Most cultivated millets use the C4 photosynthetic pathway. C4 photosynthesis is particularly advantageous under high temperature, high light intensity and water-limited conditions because it allows efficient carbon assimilation while reducing photorespiratory losses.

However, climate resilience in millets is not attributable to C4 photosynthesis alone. It is the result of several interacting physiological, morphological and phenological mechanisms [1,2].

3.2 Drought tolerance

Drought is one of the major limitations to agricultural production in semi-arid environments. Pearl millet demonstrates considerable adaptation to water limitation, and drought response has been an important target of breeding programmes [2]. Drought-adaptive characteristics include efficient root systems, appropriate phenology, maintenance of physiological activity under water stress and the ability to produce grain under relatively low rainfall. The timing, duration and intensity of drought strongly influence crop response, and therefore drought tolerance should be evaluated under realistic target environments [2].

3.3 Heat tolerance

High temperature can adversely affect flowering, pollen viability, grain set and grain filling in many cereal crops. Pearl millet is particularly adapted to high-temperature environments and can maintain reproductive development under conditions that can severely affect sensitive cereals [8]. The combination of heat and drought tolerance is particularly important because these stresses frequently occur simultaneously in dryland agricultural systems.

3.4 Short growth duration

The relatively short growth cycle of several millet species can provide an opportunity to escape terminal drought. Early-maturing varieties may complete critical reproductive stages before soil moisture becomes severely limiting. Short duration can also allow millets to fit into multiple-cropping and contingency-production systems where growing seasons are restricted.

3.3 Heat adaptation

High temperature can impair pollen viability, flowering, grain set and grain filling in many cereals. Pearl millet is particularly adapted to high-temperature environments and can maintain reproductive development under temperatures that severely affect some cool-season cereals. The combination of heat adaptation and drought tolerance is particularly valuable because heat and water stress frequently occur simultaneously.

4. Conceptual Framework

Climate Change
↓
Heat + Drought + Rainfall Variability
↓
MILLETS
↓
Stress Tolerance + Resource Efficiency
↓
Crop Diversification
↓
Soil & Water Conservation
↓
Food & Nutrition Security
↓
Farmer Resilience
↓
Sustainable Agriculture

Figure 01: Simplified conceptual framework illustrating the role of millets in climate adaptation, crop diversification, resource conservation, food and nutrition security, and sustainable agriculture.

5. Millets and Resource-Use Efficiency

5.1 Water-use efficiency

Water scarcity is becoming an increasingly important limitation to agricultural production. The adaptation of millets to rainfed and semi-arid environments makes them useful components of strategies designed to reduce dependence on irrigation. The value of millets should, however, be considered within the local farming context. Complete replacement of existing crops is not necessarily required. Strategic diversification of water-demanding crops with suitable millet species may provide a more practical pathway.

5.2 Nutrient-use efficiency

Millets can produce grain under relatively low-input conditions and can therefore be suitable for resource-constrained farming systems [1,8]. Their performance under low fertility is particularly relevant to smallholder agriculture. Nevertheless, low-input cultivation should not result in nutrient depletion. Continuous harvesting removes nutrients from agricultural soils, and therefore millet-based systems should incorporate organic amendments, crop residues, biological nutrient sources and balanced mineral fertilizers where appropriate.

5.3 Soil conservation

Millet crops can contribute to soil protection through canopy cover, root development and residue production. When combined with reduced tillage, residue retention, contour cultivation and crop rotation, millet cultivation can form part of integrated soil-conservation strategies.

6. Millets in Diversified Cropping Systems

6.1 Crop rotation

Crop rotation can reduce dependence on a single cereal and distribute production risk. Introducing millets into cereal-based rotations may also diversify rooting patterns and crop phenology.

6.2 Millet–legume systems

Millet–legume systems have potential to combine cereal and legume nutritional benefits while improving land-use efficiency. Legumes can contribute biological nitrogen fixation, whereas millet provides grain and, in some systems, valuable fodder.

6.3 Intercropping

Intercropping millets with legumes can distribute climatic risk between crops. Differences in rooting depth, canopy development and water requirements may improve the efficiency with which available resources are used.

6.4 Crop–livestock integration

Millet residues can contribute to livestock feed, while livestock manure can return nutrients to agricultural land. This creates opportunities for internal nutrient recycling and diversification of farm income.

7. Nutritional Importance of Millets

Millets have considerable nutritional value in addition to their environmental adaptability. Millet grains provide carbohydrates, proteins, fats, minerals, dietary fibre and bioactive compounds [3,4]. Hassan et al. reported that millet grains contain nutritionally important compounds as well as phenolic constituents with antioxidant activity [3]. Nutritional composition differs among species and genotypes, emphasizing the importance of genetic diversity when selecting millet varieties for specific food and nutritional applications. Pearl millet is particularly relevant to micronutrient security because breeding programmes have targeted grain iron and zinc concentrations [8,9]. Variation in grain iron and zinc among pearl millet genotypes demonstrates the possibility of improving nutritional quality through breeding [9]. Processing also affects the nutritional characteristics of millet. Decortication, milling, soaking, germination, malting and fermentation can modify nutrient availability, functional properties and antinutritional components [4].

8. Post-Harvest Processing and Value Addition

Post-harvest processing represents an important determinant of millet utilization and profitability. Traditional and modern processing methods include dehulling, soaking, germination, malting, milling, fermentation, roasting and extrusion. Yousaf et al. reviewed processing effects on millet grains and reported that processing can substantially alter nutritional and functional properties [4]. These changes provide opportunities to develop products with improved convenience and consumer acceptance.

Potential millet-based products include:

- flour;
- malt;
- flakes;
- breakfast cereals;
- bakery products;
- noodles;
- extruded foods;
- snacks;
- fermented products; and
- ready-to-cook foods.

The development of decentralized processing facilities can reduce post-harvest losses, create rural employment and increase the economic value of millet production.

9. Genetic Improvement and Genomic Approaches

9.1 Genetic diversity

Genetic diversity is a fundamental resource for improving climate resilience. Breeding programmes can exploit variation for drought tolerance, heat tolerance, disease resistance, early maturity, yield stability, nutritional quality and processing characteristics.

9.2 Drought-resilient pearl millet breeding

Drought tolerance has been a major breeding objective in pearl millet. Srivastava et al. summarized conventional and genomic approaches for improving drought tolerance and highlighted the importance of adapted germplasm, high-throughput phenotyping, marker-trait associations and genomic selection [2]. The use of adapted germplasm is particularly important because performance under drought is strongly influenced by the interaction between genotype and target environment [2].

9.3 Genomic resources

The sequencing of the pearl millet genome has substantially expanded opportunities for molecular breeding. Varshney et al. reported a draft genome of approximately 1.79 Gb and analyzed 994 pearl millet lines to characterize genetic diversity and identify resources for breeding [6]. These genomic resources provide opportunities for marker-assisted selection, genomic selection and identification of genomic regions associated with agronomic adaptation.

9.4 Genome editing

Genome-editing technologies provide additional opportunities to modify specific traits. However, genome editing should be integrated with conventional breeding, germplasm evaluation and field-based phenotyping rather than viewed as an independent solution [1,7].

10. Major Millet Species and Their Potential

Table 01: Major millet species and their potential contribution to climate-resilient agriculture

Millet	Scientific name	Important adaptive characteristics	Nutritional significance	Potential agricultural role
Pearl millet	Pennisetum glaucum / Cenchrus americanus	High heat and drought adaptation; C4 metabolism	Protein, minerals, fibre and bioactive compounds	Dryland grain and fodder production
Finger millet	Eleusine coracana	Adaptation to rainfed environments; tolerance of variable moisture	Particularly rich in calcium; fibre and phenolics	Nutrition-sensitive rainfed agriculture
Foxtail millet	Setaria italica	Short duration and drought adaptation	Protein, fibre and minerals	Short-season crop and diversification
Little millet	Panicum sumatrense	Adapted to rainfed and marginal environments	Fibre, minerals and phytochemicals	Low-input farming and diversification

Kodo millet	Paspalum scrobiculatum	Adaptation to marginal conditions	Fibre and phenolic compounds	Dryland diversification
Barnyard millet	Echinochloa spp.	Short duration and environmental adaptability	Fibre, minerals and protein	Contingency and diversified cropping
Proso millet	Panicum miliaceum	Short growing period and drought adaptation	Protein, fibre and minerals	Short-season and water-limited agriculture

11. Climate Stresses and Millet-Based Management Responses

Table 02: Major climatic stresses, millet responses and management options

Climate stress	Potential production effect	Millet-related advantage	Recommended intervention	Expected benefit
Drought	Poor establishment and reduced grain filling	Drought adaptation and efficient water utilization	Drought-tolerant varieties, timely sowing and moisture conservation	Improved yield stability
High temperature	Reduced flowering and grain set	Heat adaptation, particularly in pearl millet	Heat-tolerant breeding and appropriate sowing time	Greater reproductive stability
Erratic rainfall	Crop establishment failure or terminal drought	Short-duration adaptation	Rainfall-based sowing and contingency planning	Reduced climatic risk
Low soil fertility	Reduced crop growth	Performance under relatively low-input conditions	Integrated nutrient management	Improved resource efficiency
Soil erosion	Loss of soil and nutrients	Crop cover and rooting	Residue retention and conservation practices	Improved soil protection
Water scarcity	Reduced irrigation availability	Suitability for rainfed production	Water harvesting and supplemental irrigation where feasible	Reduced irrigation dependence
Pest and disease pressure	Yield losses	Genetic diversity for resistance	Resistant cultivars and integrated pest management	Reduced production losses
Climate-induced crop failure	Farm income instability	Diversification potential	Millet-legume intercropping and crop rotation	Improved livelihood resilience

12. Constraints to Wider Adoption

Despite their potential, several factors limit the wider adoption of millets.

12.1 Seed availability

Farmers require reliable access to high-quality seed of varieties adapted to local environments. Strengthening formal and community seed systems can improve adoption.

12.2 Mechanization

Harvesting, threshing, cleaning and dehulling can be labour-intensive. Limited availability of suitable machinery increases production and processing costs.

12.3 Market limitations

Farmers may face weak or fragmented markets for millet grain. Stable procurement, aggregation, branding and value-added processing can improve economic returns.

12.4 Consumer preferences

Changing dietary preferences can reduce demand for traditional millet foods. Convenient and affordable products may increase consumer acceptance.

12.5 Processing constraints

The absence of local dehulling and milling facilities can increase processing costs and discourage production, particularly for small millets.

13. Research and Development Priorities

Table 03: Research and development priorities for millet-based sustainable agriculture.

Area	Existing challenge	Priority intervention	Expected outcome
Breeding	Yield instability under severe stress	Selection for combined drought and heat tolerance	Climate-resilient varieties
Genomics	Limited genomic resources for some species	GWAS, genomic selection and genome editing	Faster genetic improvement
Seed systems	Limited access to quality seed	Community and formal seed multiplication	Increased adoption
Agronomy	Farmer-level yield gaps	Improved sowing, nutrient and moisture management	Higher productivity
Mechanization	Labour-intensive operations	Affordable smallholder machinery	Reduced production cost
Processing	Dehulling and milling constraints	Village-level processing units	Increased value addition
Food technology	Limited convenient products	Ready-to-cook and ready-to-eat products	Increased consumer demand
Markets	Price uncertainty	Procurement and organized value chains	Improved farm income
Extension	Limited technical awareness	Farmer demonstrations and digital advisories	Better technology adoption
Policy	Fragmented institutional support	Integration of millets into climate and nutrition programmes	Long-term mainstreaming

14. Millets and Nutrition Security

Climate-resilient agriculture should not focus exclusively on yield stability. Food quality and nutritional security are equally important. Millets can contribute to diversified diets through their protein, mineral, fibre and phytochemical content [3,4]. Pearl millet has particular relevance for micronutrient security because of its iron and zinc content and the existence of substantial genetic variation for these traits [8,9]. The combination of millets and legumes may be particularly useful because it brings together complementary nutritional characteristics. However, millet promotion should be viewed as part of a diversified diet rather than as a replacement for all other cereal or food crops.

15. Millets and Sustainable Food Systems

Millet-based agriculture can contribute to sustainability through several pathways. First, the adaptation of millets to rainfed environments can reduce dependence on irrigation. Second, their inclusion in diversified rotations can reduce reliance on a limited number of crops. Third, their nutritional characteristics can support dietary diversification. Fourth, processing and value addition can create rural employment opportunities. The strongest sustainability benefits are likely to occur when millet cultivation is combined with improved soil management, water conservation, crop diversification and efficient value chains rather than when millets are grown as isolated crops.

16. Future Research Priorities

Future research should address both crop-level and system-level questions.

16.1 Combined heat and drought stress

Research should increasingly examine simultaneous heat and water stress because these conditions commonly occur together in farmers' fields.

16.2 Crop modelling

Crop models can help identify suitable millet species and varieties for future climate scenarios and assist in developing regional adaptation strategies.

16.3 Genomic selection

Genomic selection can accelerate improvement of complex traits such as yield stability, drought tolerance and nutritional quality [2,6].

16.4 Nutritional improvement

Breeding programmes should combine climate adaptation with improvement of iron, zinc, calcium, protein quality and other nutritional characteristics [8,9].

16.5 Mechanization

Smallholder-compatible seeders, harvesters, threshers, cleaners and dehullers should receive greater research attention.

16.6 Processing technologies

Affordable processing technologies are necessary to improve convenience, reduce labour requirements and expand millet markets.

16.7 Sustainability assessment

Life-cycle assessment and farm-level economic studies are needed to quantify water use, energy requirements, greenhouse-gas emissions, soil impacts and profitability of millet-based systems.

17. Strategic Pathway for Mainstreaming Millets

The successful integration of millets into climate-resilient agriculture requires coordinated action across the agricultural value chain:

Climate-resilient breeding → quality seed → improved agronomy → diversified cropping systems → efficient processing → value-added products → market development → improved farmer income → resilient food systems.

This pathway highlights that millet development should not be restricted to crop breeding. Improvements in production, processing, marketing and consumer acceptance are equally important.

18. Conclusion

Millets represent a valuable group of crops for strengthening agricultural resilience under increasing climatic uncertainty. Their adaptation to heat, drought and variable rainfall, combined with their nutritional value, makes them particularly relevant to rainfed and semi-arid farming systems [1,2,8]. Their contribution to sustainable agriculture, however, extends beyond stress tolerance. Millets can become more valuable when incorporated into diversified cropping systems, millet–legume associations, integrated crop–livestock systems and soil- and water-conservation practices.

Advances in genomics have opened new opportunities for improving millet productivity, adaptation and nutritional quality. The pearl millet genome and extensive resequencing resources provide a strong foundation for molecular breeding and genomic selection [6]. Similarly, advances in processing technology can improve the nutritional and functional characteristics of millet-based foods [4]. Therefore, millets should be regarded not simply as traditional or minor cereals but as strategic crops for climate adaptation, resource conservation, food diversification and nutrition security. Their wider adoption will require coordinated investment in breeding, agronomy, seed systems, mechanization, processing, markets, extension and policy. A systems-based approach can help transform the inherent resilience of millets into practical benefits for farmers, consumers and the environment.

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