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Millets: Ancient Grains, Modern Genes and a Climate-Resilient Food Future

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Millets are increasingly recognized as strategic crops for climate-resilient agriculture, nutritional diversification and sustainable food production. Their adaptation to drought, heat, water limitation, low soil fertility and irregular rainfall, together with their genetic diversity and nutritional value, makes them valuable resources for future crop improvement. Millets provide carbohydrates, protein, dietary fibre, minerals, B vitamins and diverse bioactive compounds, while their landraces and breeding materials offer opportunities to improve stress tolerance, yield, grain quality and nutritional traits. Recent advances in genomics, genome-wide association studies (GWAS), multi-omics, artificial intelligence (AI), high-throughput phenotyping, genomic selection and genome editing are creating new opportunities for faster and more precise millet improvement. At the same time, better agronomy, mechanization, processing, value addition and stronger market linkages are needed to convert genetic potential into farmer and consumer benefits. This article highlights the genetic, nutritional and climate-resilience potential of millets and discusses how modern breeding technologies can complement traditional genetic resources. An integrated seed-to-consumer approach can help develop millet varieties that combine high and stable productivity, climate resilience, nutritional quality, consumer acceptance and market value, strengthening the role of millets in future sustainable agriculture.

Keywords: Millets; climate-resilient agriculture; genetic diversity; genomics; GWAS; multi-omics; artificial intelligence; high-throughput phenotyping; genome editing; nutritional security; precision breeding; value addition

Introduction

Millets are no longer viewed only as traditional cereals of dryland farming. They are emerging as strategic crops for a changing agriculture because many species can produce food under relatively low-input, rainfed and stressful environments. Drought, heat, water scarcity, soil degradation and irregular rainfall are increasingly challenging crop production, while consumers and policymakers are also demanding greater nutritional diversity. Millets bring these two needs together: they offer valuable genetic diversity for crop improvement and provide carbohydrates, protein, dietary fibre, minerals, B vitamins and diverse bioactive compounds. The next opportunity is to combine their traditional resilience with modern genetics, genomics, precision breeding, improved agronomy and value addition. The evidence also calls for a balanced interpretation: resilience is species- and genotype-dependent, and performance under farmers' conditions depends on rainfall timing, soil, pests, seed quality and management. Millets are therefore best viewed as components of diversified, locally adapted farming systems—not as universal substitutes for rice or wheat.

Millets: A Diverse Genetic Portfolio

'Millets' is an umbrella term, not a single crop. Millets are small-seeded cereals belonging mainly to the grass family Poaceae. Major millets include pearl millet, finger millet, foxtail millet and proso millet, while small millets include little, kodo, barnyard and browntop millet. These species differ in maturity duration, adaptation, grain composition and stress response. Therefore, the term "millet" represents a diverse genetic portfolio rather than a single crop.

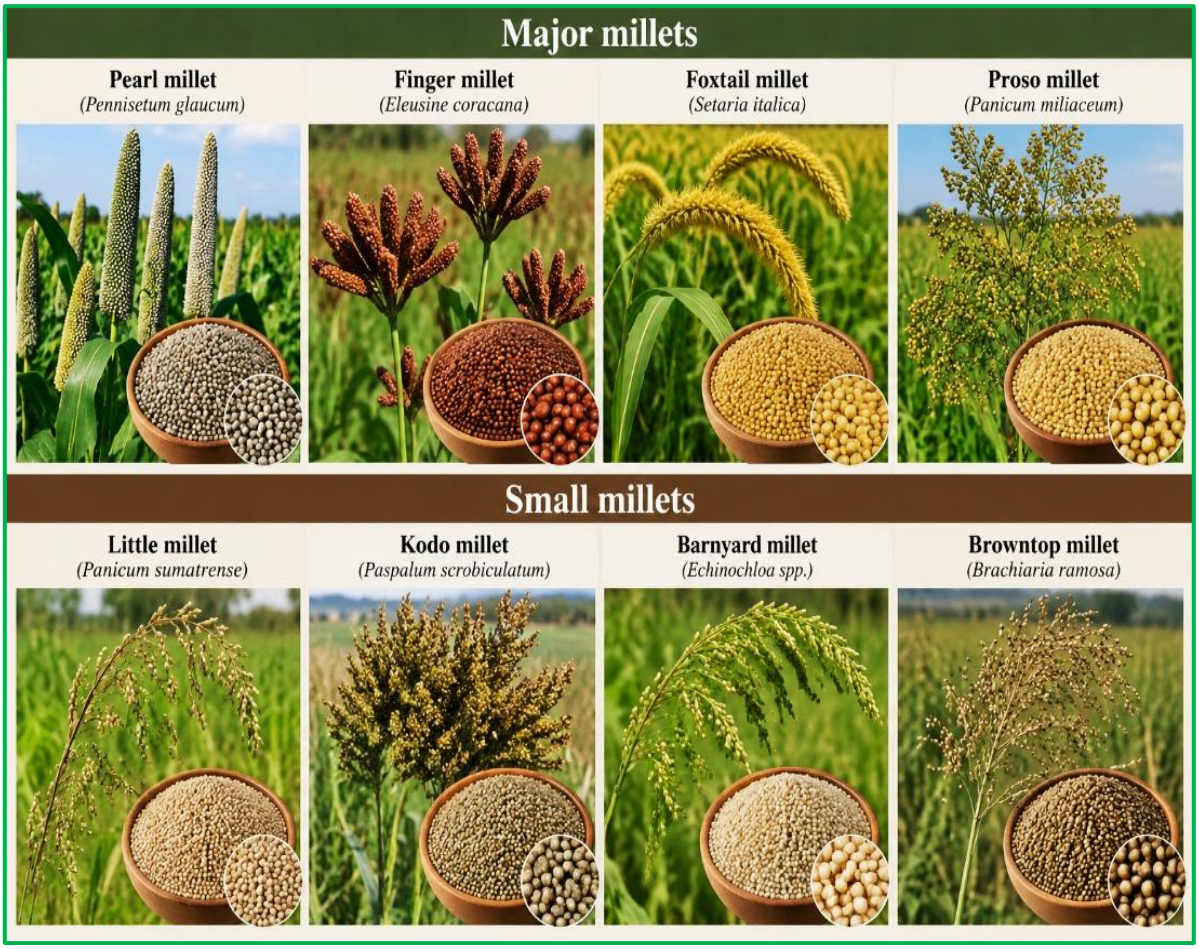

Figure 1. Major and small millets and their grain diversity.

Why Are Millets Important in the Climate-Change Era?

Millet production systems are often associated with rainfed and water-limited environments. Depending on species and genotype, millets can show adaptation to drought, heat, low soil fertility, salinity, intermittent rainfall and water limitation. Their relatively short duration can also make them useful components of diversified cropping systems. However, millets are not "climate-proof" crops. Severe heat, drought, pests, diseases and poor management can still cause substantial yield losses. Climate resilience should therefore be understood as comparatively better adaptation and the potential for more stable production under difficult environments, not immunity to climate stress. For farmers, the practical opportunity is to match the right millet to the right location. Timely sowing, suitable seed rate, weed control, balanced nutrient management, moisture conservation and locally recommended varieties remain essential. Millets should complement, not automatically replace other crops. Their greatest contribution may come from diversified rotations and mixed farming systems that spread weather and market risk. Figure 3 summarizes how genetic resources and breeding technologies can connect climate challenges to consumer benefits. A useful climate-resilience strategy should evaluate yield stability across locations and seasons, not just maximum yield in one trial. Breeders should combine stress adaptation with farmer-preferred maturity, grain quality, fodder value and suitability for local food products. Multi-environment testing is essential before recommending a variety beyond its target production zone.

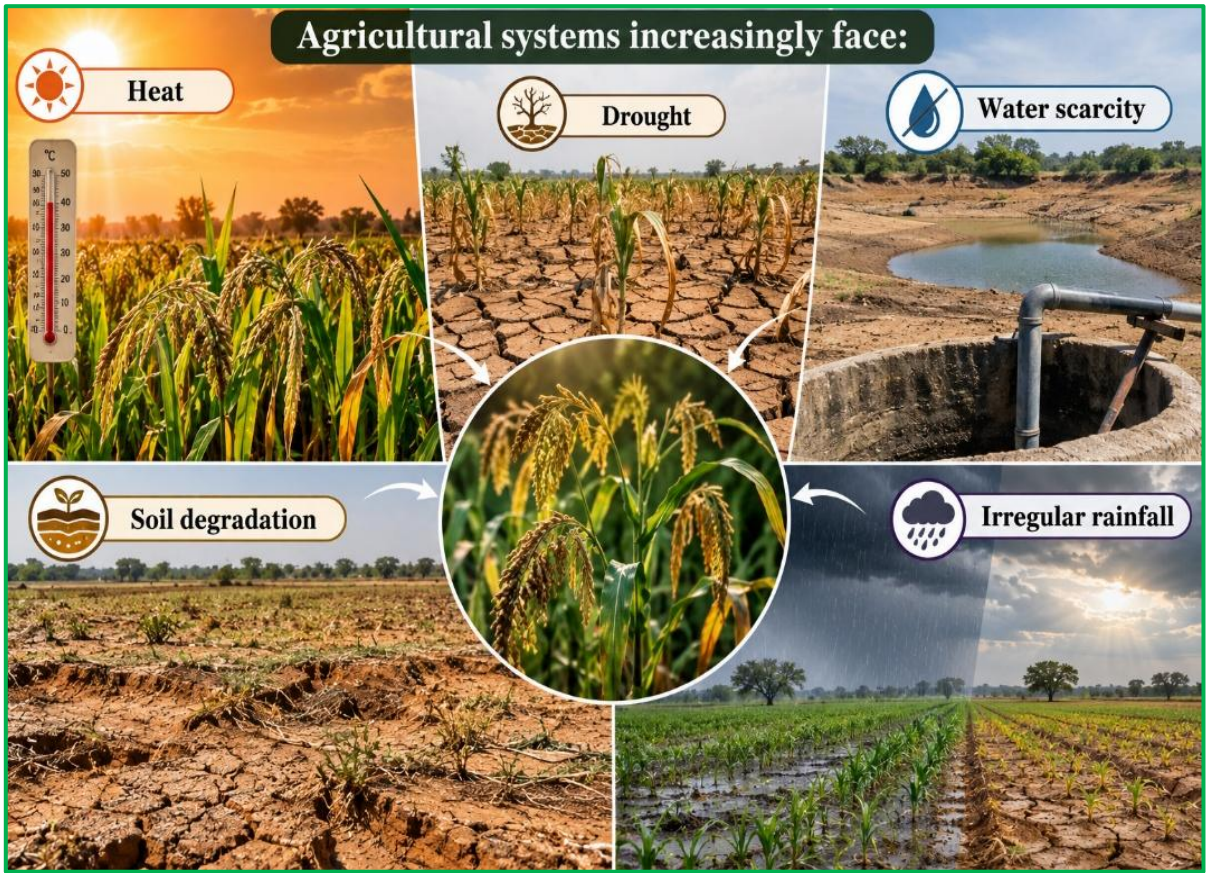

Figure 2. Major stresses affecting agricultural production under climate change.

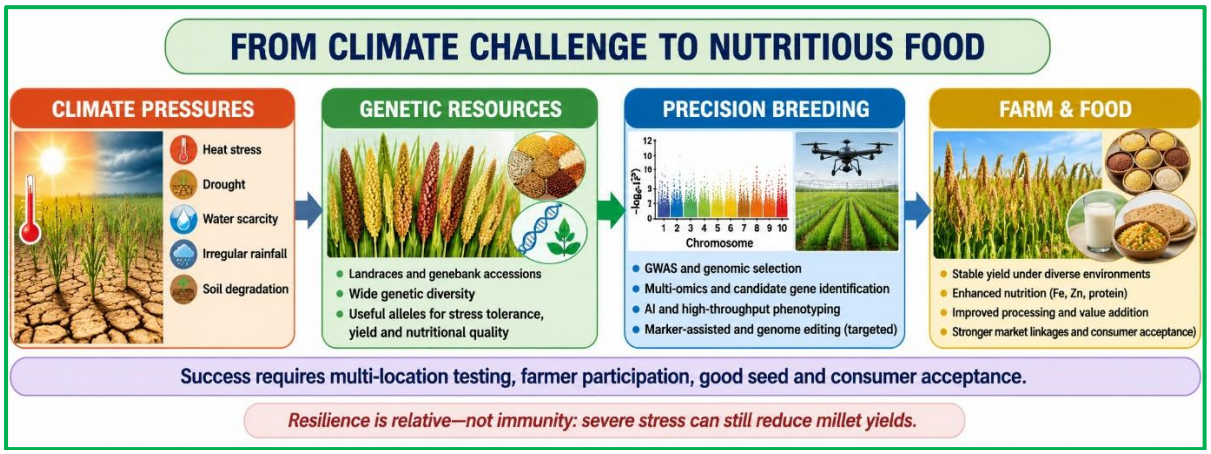

Figure 3. A seed-to-consumer pathway linking climate challenges, genetic resources and precision breeding.

Nutrition: More Than Calories

Millets can contribute to dietary diversification because their nutritional composition includes carbohydrates, protein, dietary fibre, minerals, B vitamins, phenolic compounds and other bioactive components (Figure 4). Finger millet is particularly notable for its calcium concentration. However, nutritional value varies with species, genotype, environment and processing. Consequently, millets should be promoted as nutritionally valuable whole grains rather than as universal cures for diseases. Their health contribution depends on genotype, processing, quantity consumed and the overall dietary pattern. Nutrition claims should also distinguish total nutrient concentration from bioavailability. Phytate and other anti-nutritional factors, as well as dehulling, milling, soaking, germination and fermentation, can affect the amount of minerals available to the body. Breeding for nutrient density should therefore be paired with food-processing research and clear, evidence-based nutrition communication.

Figure 4. Nutritional components and potential dietary contributions of millets.

Table 1. Millet opportunities for future agriculture

Area	Future opportunity
Climate	Adaptation to many dryland and water-limited environments
Nutrition	Protein, fibre, minerals and diverse bioactive compounds
Genetic resources	Large diversity across species, landraces and breeding materials
Breeding	Use of genomic tools, multi-omics, genomic selection and targeted editing
Technology	Artificial intelligence and high-throughput phenotyping for faster selection
Value addition	Flour, bakery foods, snacks, beverages, fermented and ready-to-cook products

The Hidden Treasure: Genetic Diversity

The greatest scientific value of millets may lie in their genetic diversity. Traditional varieties and landraces have evolved under diverse environments and farming systems and may carry useful alleles for drought adaptation, heat tolerance, disease resistance, early maturity, nutrient accumulation, root traits, grain quality and biomass production. Conservation must therefore move beyond storage. A useful sequence is: collection → characterization → conservation → genotyping → phenotyping → breeding. Genebanks can thus serve as repositories of potential solutions to future agricultural problems. This diversity becomes useful only when it is documented and made accessible. Core collections, passport data, standardized phenotyping and seed multiplication can help breeders identify promising donors. Genotyping and genome sequencing can then connect visible variation with underlying alleles, while conserving landraces in genebanks and on farms protects options that may become important under future climates.

From Conventional Selection to Precision Millet Breeding

Modern millet improvement is progressing from conventional selection toward increasingly precise genetic approaches. Genome-wide association studies (GWAS) can associate natural genetic variation with traits such as plant height, flowering time, yield, tillering, stress

tolerance, disease resistance, iron and zinc concentration, protein content and grain quality. The key challenge is to move from a significant genetic marker to a candidate region, candidate gene, functional validation and finally a breeding application. For complex traits such as grain yield, drought response and iron or zinc concentration, no single marker or technology is likely to provide a complete solution. Genome-wide association studies (GWAS) identify marker–trait associations, while genomic selection predicts breeding value using genome-wide markers. Both require representative populations, reliable phenotypes and validation across environments. Candidate genes should be treated as hypotheses until supported by functional evidence and breeding validation.

Multi-omics strengthens this process. Genomics asks what genetic variation exists; transcriptomics examines gene expression; proteomics identifies proteins; metabolomics reveals biochemical changes; and epigenomics helps explain gene regulation. Integrating these approaches can improve understanding of complex traits such as drought tolerance and nutritional quality. Historically, millet improvement depended heavily on farmer selection. Modern breeding adds several layers of precision.

Conventional breeding

Selection → Hybridization → Segregation → Selection → Evaluation

Marker-assisted breeding

Trait → QTL → Marker → Selection

Genomic breeding

Genome-wide markers → Prediction → Selection

Precision breeding

Gene/allele discovery → functional validation → targeted modification

This progression provides an opportunity to accelerate genetic gain while retaining the diversity accumulated through traditional agriculture.

Artificial Intelligence and High-Throughput Phenotyping

Artificial intelligence (AI) can become a powerful decision-support tool in millet breeding when it is combined with reliable biological data. Images from cameras, smartphones, drones and other sensors can support plant counting, height estimation, disease detection, biomass prediction, stress classification and yield prediction. Breeding decisions may increasingly combine DNA, images, environmental data, machine learning and field observations. High-throughput phenotyping complements genomics through RGB, multispectral and hyperspectral imaging, thermal cameras, unmanned aerial vehicles and automated platforms. The basic principle is simple: genotype + phenotype + environment = predictive breeding. AI should support, not replace field experimentation and breeder judgement. Models trained in one location or season may perform poorly under different lighting, soils, genotypes or management. Their value depends on representative training data, independent validation, affordable tools and workflows that farmers and breeding teams can actually use.

Genome Editing: Designing Better Millets

Genome editing offers the possibility of modifying specific genes or alleles associated with useful traits. CRISPR/Cas9, Cas12a, base editing, prime editing and multiplex editing are potential tools for targets such as disease resistance, plant architecture, flowering time, grain quality, nutritional composition and stress tolerance. In millets, transformation and regeneration remain important constraints for several species. Therefore, the practical question is not only whether a gene can be edited, but whether the edited genotype can be efficiently regenerated, evaluated and deployed in diverse genetic backgrounds.

From Seed to Consumer: The Missing Link

Improving production alone will not guarantee wider millet consumption. Consumers increasingly expect convenience, attractive products, consistent quality, easy cooking and competitive prices. Processing can include dehulling, milling, soaking, germination or malting, fermentation, flaking, popping and extrusion. Value-added products include ready-to-cook

foods, breakfast cereals, bakery products, noodles, snacks, fermented foods, beverages and composite flours. Millet improvement should therefore consider the entire chain: **seed → farm → grain → processing → product → consumer**.

Major Constraints and the Road Ahead

Despite strong potential, millet development faces limited access to quality seed, inadequate mechanization, low productivity in many production systems, weed competition, pests and diseases, fragmented value chains, limited processing infrastructure and inconsistent markets. Consumer preference for rice and wheat also remains an important challenge. The future strategy should connect genetic improvement with location-specific agronomy, mechanization, processing, entrepreneurship and stronger market linkages. A future precision-breeding pipeline can integrate traditional diversity, genebanks and wild relatives with genomics or pangenomics, GWAS and quantitative trait locus analysis, multi-omics, candidate-gene validation, AI and genomic prediction, high-throughput phenotyping, genomic selection, genome editing, speed breeding and multi-environment testing. The target should be a multi-trait millet ideotype that combines high and stable yield, drought and heat tolerance, disease resistance, nutrient density, suitable maturity, efficient water and nutrient use, lodging resistance, mechanized harvestability and good grain and processing quality.

Conclusion

Millets represent a rare combination of ancient agricultural heritage and modern scientific opportunity. Their value comes from genetic diversity, environmental adaptation, nutritional potential and suitability for diversified farming systems. Yet traditional resilience alone is not enough. The next phase of millet improvement must combine farmer knowledge and genetic resources with genomics, GWAS, multi-omics, AI, high-throughput phenotyping, genome editing, speed breeding, improved agronomy and value addition. If these components are connected across the seed-to-consumer chain, millets can become more productive, profitable, nutritious and climate-resilient crops. The real opportunity is not simply to bring an ancient grain back to the table, but to redesign millet agriculture for a hotter, more water-constrained and nutritionally demanding world.

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