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Exploring Millet Genetic Diversity for Improved Crop Resilience: A Review

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Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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Review Article

ABSTRACT

This review comprehensively explores the genetic diversity of millets in India and its pivotal role in enhancing crop resilience, adapting to climate change, and contributing to nutritional security. Millets, with their remarkable adaptability to diverse agro-ecological conditions, are integral to India's agricultural landscape. The review starts by providing an overview of the various types of

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millets cultivated in India, including pearl millet (*Pennisetum glaucum*), finger millet (*Eleusine coracana*), and foxtail millet (*Setaria italica*), highlighting their nutritional and environmental benefits and their historical and cultural significance. The core of the review delves into the genetic structure and variability among millet species, examining both intra-species and inter-species diversity. It emphasizes the importance of conserving this genetic diversity, which is currently threatened by factors such as genetic erosion and limited access to genetic resources. The review discusses the advances in millet breeding techniques, from conventional approaches to biotechnological interventions, and underscores the importance of integrating traditional agricultural knowledge with modern science. A series of case studies from India illustrates the successful examples of millet genetic improvement, the lessons learned from past breeding programs, and the tangible impacts of improved millet varieties on farming communities. These case studies highlight the development of drought-resistant, pest-resistant, and nutritionally enhanced millet varieties, demonstrating the benefits of genetic diversity in practical terms. Looking forward, the review identifies emerging trends in millet research in India, including the increasing focus on genomics and bioinformatics, climate-smart agriculture, and the enhancement of the nutritional qualities of millets. It also addresses the policy and funding considerations vital for advancing millet research, emphasizing the need for supportive policies that promote the cultivation and consumption of millets and the importance of funding for research focused on genetic improvement and climate resilience.

Keywords: Genetics diversity; millet; climate change adaptation; nutritional resilience.

1. INTRODUCTION

Millets are a group of highly variable small-seeded grasses, widely grown around the world as cereal crops or grains for both human food and fodder. They are particularly important in arid and semi-arid regions due to their resistance to drought and poor soil fertility. Millets include species like pearl millet (*Pennisetum glaucum*), finger millet (*Eleusine coracana*), and foxtail millet (*Setaria italica*), among others. Their global significance lies not only in their adaptability to challenging growing conditions but also in their nutritional benefits, as they are rich in vitamins, minerals, and fiber [1]. In countries like India, millets have been a traditional staple for centuries, underscoring their cultural as well as nutritional importance. Genetic diversity refers to the total number of genetic characteristics in the genetic makeup of a species. It is essential for a species' ability to adapt to changing environmental conditions and to survive. In the context of agriculture, crop resilience is the ability of crops to maintain yield and quality under diverse and adverse environmental conditions. Genetic diversity in millets plays a crucial role in this resilience, offering a buffer against pests, diseases, and climate change [2]. It also provides the raw material for breeding programs aimed at developing improved varieties. The objectives of this review are threefold: Summarize Current Knowledge on Millet Genetic Diversity, Discuss the Role of This Diversity in Enhancing Crop Resilience, Identify Gaps in Research and Potential Areas for Future Studies.

2. MILLETS

A. Types of Millets and Their Geographic Distribution

In India, millets are an integral part of the agrarian landscape, playing a crucial role in the food security and agricultural diversity of the country. Major types of millets cultivated in India include pearl millet (*Pennisetum glaucum*), known locally as 'Bajra', predominantly grown in arid and semi-arid regions such as Rajasthan and Maharashtra. Finger millet (Eleusine coracana), or 'Ragi', is primarily cultivated in Karnataka, Uttarakhand, and Tamil Nadu. Foxtail millet (*Setaria italica*), known as 'Kangni' or 'Navane', is commonly grown in states like Andhra Pradesh and Telangana. Other varieties such as little millet (*Panicum sumatrense*), barnyard millet (*Echinochloa* spp.), and kodo millet (*Paspalum scrobiculatum*) are also grown in various parts of the country, particularly in regions where the terrain is rugged and the climate harsh [3].

B. Nutritional and Environmental Benefits of Millets

Millets are highly nutritious, providing a rich source of fiber, proteins, vitamins, and minerals. They have a low glycemic index, which makes them beneficial for people with diabetes – a significant health concern in India. For instance, finger millet is rich in calcium and iron, making it an essential diet component for combating anemia and osteoporosis [4]. From an environmental perspective, millets are hardy crops requiring minimal inputs. They are well adapted to a range of ecological conditions, often thriving in poor soil fertility and with low water requirements. This makes them a sustainable crop choice in the face of climate change, particularly in the drought-prone areas of India.

C. Historical and Cultural Significance of Millets

Millets hold a venerable position in India's agricultural and cultural history. They have been cultivated for thousands of years, with their importance reflected in various traditional cuisines and cultural practices. Millets are often used in traditional dishes, especially in rural and tribal areas. Festivals in different parts of India, like Sankranti in South India, often feature dishes made from millets, highlighting their cultural significance. The recent revival of interest in millets is not just a nod to their health benefits but also a reconnection with a heritage that has revered these grains for generations [5].

3. GENETIC DIVERSITY IN MILLETS

A. Genetic Structure and Variability Among Millet Species

In India, millets exhibit a remarkable range of genetic diversity, both within and between species. This diversity is a result of the varied agro-ecological zones across the country, coupled with traditional farming practices and evolutionary processes. Within a single millet species, like pearl millet or finger millet, there exists a substantial level of genetic variation. This is evident in the numerous local varieties and landraces found across different regions of India. For instance, pearl millet in Rajasthan shows significant variation in drought tolerance, grain color, and nutritional content compared to those grown in Maharashtra [6]. When considering different species of millets, the genetic variability becomes even more pronounced. Each species, adapted to specific climatic and soil conditions, has developed unique traits. Foxtail millet, predominantly grown in southern India, differs significantly in its genetic makeup from barnyard millet, which is more common in the northern regions.

B. Sources of Genetic Diversity

The genetic diversity of millets in India stems from various sources, ensuring their adaptability and resilience. Wild relatives of cultivated millets serve as a genetic reservoir, often containing traits for disease resistance and stress tolerance. Landraces, developed over generations by farmers, also contribute to genetic diversity. These traditional varieties, adapted to local conditions, are a testament to the agricultural heritage and biodiversity of India. Spontaneous genetic mutations and selective breeding have also played roles in shaping the genetic diversity of millets. In India, breeding programs, both government-led and community-based, have developed new varieties with improved yield, nutritional quality, and stress tolerance.

C. Methods of Assessing Genetic Diversity

Assessing the genetic diversity in millets involves a combination of traditional and modern techniques. Techniques like RAPD (Random Amplified Polymorphic DNA) and AFLP (Amplified Fragment Length Polymorphism) have been used to study genetic variation within millet populations in India. These molecular markers help in understanding the genetic relationships and diversity patterns among different varieties [7]. With advances in genomic technology, more sophisticated methods like genome sequencing and GWAS (Genome-Wide Association Studies) are being employed. These approaches offer deeper insights into the genetic architecture of traits like drought tolerance and nutrient content in millets. Alongside molecular techniques, phenotypic evaluations of millets, observing physical traits like plant height, grain size, and color, continue to be crucial in understanding and utilizing genetic diversity. Such evaluations, often conducted in field trials, provide practical insights into the performance of different millet varieties under various environmental conditions.

4. ROLE OF GENETIC DIVERSITY IN CROP RESILIENCE

A. Stress Tolerance in Millets

In India, millets are celebrated for their remarkable stress tolerance, attributed largely to their genetic diversity. This tolerance is crucial in sustaining agriculture in various stress-prone regions across the country. Millets, particularly pearl millet and sorghum, have evolved mechanisms to withstand prolonged periods of drought. This resilience is of paramount importance in arid and semi-arid regions like Rajasthan and parts of Maharashtra, where water scarcity is a major limiting factor for agriculture. The genetic diversity within these species allows them to maintain productivity and survive in low-moisture conditions [8]. The genetic variability in millets also provides resistance against a range of pests and diseases. For instance, certain varieties of finger millet in Southern India exhibit resistance to blast disease, a major threat to millet crops. This resistance is a direct result of the genetic diversity inherent in these traditional varieties [9]. Millets are known for their ability to thrive in nutrient-poor, marginal soils where other crops would fail. This is particularly relevant in the tribal belts of central India, where soil fertility is often low. The genetic adaptability of millets allows them to utilize nutrients efficiently and grow in less-than-ideal soil conditions.

B. Climate Change Adaptation

The inherent genetic diversity of millets makes them well-suited to adapt to the challenges posed by climate change, especially in a country like India, which faces diverse climatic challenges. Millets have shown a remarkable capacity to adapt to varying temperatures. In the northern plains of India, where temperature fluctuations between seasons are significant, millets like foxtail and barnyard exhibit resilience, adjusting their growth cycles to the prevailing temperatures [10]. With changing rainfall patterns due to climate change, millets' ability to grow under low water availability becomes increasingly important. In regions like Tamil Nadu and Andhra Pradesh, where rainfall is unpredictable, the cultivation of millets ensures food security and agricultural sustainability.

C. Nutritional Resilience

Genetic diversity in millets not only contributes to their adaptability to environmental stresses but also to their nutritional profile. Unlike many other crops, millets can maintain their nutritional quality even under stress conditions. For example, in drought conditions, pearl millet and finger millet still produce grains with high nutritional value, providing essential nutrients like iron and calcium to the population [11]. Leveraging genetic diversity for biofortification is a promising approach to enhancing the nutritional value of millets. In India, breeding programs are focusing on developing millet varieties with increased micronutrient content, utilizing the genetic variability present within these species.

5. CHALLENGES AND OPPORTUNITIES IN MILLET BREEDING

A. Challenges in Conserving and Utilizing Genetic Diversity

The conservation and utilization of millet genetic diversity in India face several challenges. One of the major concerns in India is the loss of genetic diversity, often referred to as genetic erosion. This occurs due to the replacement of traditional varieties with high-yielding, commercially viable ones. The shift towards monoculture in many agricultural regions has led to a decrease in the cultivation of diverse millet varieties, particularly those that were once widely grown in semi-arid and arid regions [12]. Another significant challenge is the limited access to existing genetic resources. While India boasts several gene banks and research institutions, the accessibility of these resources for breeding and research purposes is often constrained by regulatory, logistical, and intellectual property issues. This hampers the efforts to utilize the existing genetic diversity in breeding programs [13].

B. Advances in Breeding Techniques

Despite these challenges, India has seen significant advances in millet breeding techniques. Conventional breeding, involving the selection of desirable traits and cross-breeding, remains a cornerstone in millet improvement programs. These methods have been successful in developing varieties with improved yield, disease resistance, and stress tolerance. For instance, the development of high-yielding pearl millet varieties suited to Indian climates has been a significant achievement of conventional breeding [14]. Recent advances in biotechnology have opened new avenues in millet breeding. Techniques such as marker-assisted selection (MAS) and genomic selection are being explored to expedite the breeding process. These approaches allow for the precise identification and incorporation of beneficial traits, thereby enhancing the efficiency of breeding programs [15].

Table 1. Genetic diversity in millets

Millet Type	Genetic Variability	Notable Traits	Geographical Distribution
Pearl Millet (*Pennisetum glaucum*)	High; diverse gene pool	Drought-resistant, high temperature tolerant	Widely grown in Africa, India, and parts of the Middle East
Finger Millet (*Eleusine coracana*)	Moderate; several distinct varieties	Rich in calcium, drought-resistant	East Africa, India, Nepal
Foxtail Millet (*Setaria italica*)	High; various landraces and cultivated varieties	Short growing season, pest resistant	Asia, Europe, North and East Africa
Proso Millet (*Panicum miliaceum*)	Moderate; limited genetic study	Short growing season, adaptable to poor soils	Central and East Asia, Eastern Europe, USA
Barnyard Millet (*Echinochloa* spp.)	Low to Moderate; fewer varieties compared to others	Gluten-free, high fiber content	India, Japan, China
Little Millet (*Panicum sumatrense*)	Moderate; diverse in wild relatives	Tolerant to infertile soils, quick maturing	Widespread in India, Nepal, and Sri Lanka
Kodo Millet (*Paspalum scrobiculatum*)	Moderate; includes wild and cultivated varieties	Drought-resistant, nutritious	India, West Africa, Philippines
Teff Millet (*Eragrostis* tef)	Low to Moderate; relatively narrow genetic base	Gluten-free, high in iron and calcium	Primarily Ethiopia, Eritrea

Table 2. Nutritional resilience of millets

Millet Type	Nutritional Profile	Health Benefits	Role in Food Security
Pearl Millet	High in protein, fiber, iron, zinc, and B vitamins.	Supports immune function, aids in digestion, energy provision.	Ideal in drought-prone areas due to its high nutritional value and hardiness.
Finger Millet	Rich in calcium, iron, protein, and amino acids.	Bone health, anemia prevention, supports muscle health.	Valuable in areas with calcium-deficient diets; good storability enhances availability.
Foxtail Millet	Contains protein, dietary fiber, minerals, and B vitamins.	Heart health, diabetes control, digestive health.	Adapts well to different climates, ensuring a consistent food source.
Proso Millet	Good source of protein, phosphorus, and lecithin.	Supports brain health, aids in tissue repair, energy provision.	Short growing cycle ensures rapid availability in varied environments.
Barnyard Millet	High fiber content, low glycemic index, gluten-free.	Weight management, blood sugar control, celiac-friendly.	Fast-growing, ensuring quick harvest and food supply.
Little Millet	Rich in fiber, B vitamins, minerals, and antioxidants.	Digestive health, antioxidant benefits, energy provision.	Thrives in poor soil, providing a reliable food source in marginal lands.
Kodo Millet	High in fiber, vitamins, and minerals, especially iron and calcium.	Bone health, anemia prevention, aids in digestion.	Drought-resistant, suitable for cultivation in nutrient-poor soils.
Teff Millet	Excellent source of protein, calcium, iron, and amino acids.	Muscle development, bone health, anemia prevention.	Grows in various climates, important for regions with limited crop choices.

C. Integrating Traditional Knowledge and Modern Science

An emerging trend in Indian millet breeding is the integration of traditional agricultural knowledge with modern scientific methods. Recognizing the value of indigenous knowledge in understanding the adaptability and resilience of traditional millet varieties, researchers and breeders are increasingly collaborating with local communities. This collaborative approach ensures the conservation of traditional varieties and their unique traits while applying scientific methods to improve them further [16].

6. CASE STUDIES

A. Successful Examples of Millet Genetic Improvement

India has witnessed several successful instances of millet genetic improvement, showcasing the potential of breeding and biotechnological approaches. One notable example is the development of improved pearl millet hybrids like HHB 67 Improved, which was developed by Haryana Agricultural University. This variety was specifically bred for resistance to downy mildew, a devastating disease for pearl millet. Its introduction not only led to increased yields but also demonstrated the effectiveness of targeted breeding programs in addressing specific agricultural challenges [17]. Another success story is the development of biofortified finger millet varieties with enhanced calcium content. These varieties, developed through collaborative efforts between Indian agricultural research institutes and international organizations, aim to address nutritional deficiencies prevalent in rural populations, particularly among women and children [18].

B. Impact of Improved Varieties on Farming Communities

The introduction of improved millet varieties has had a significant impact on farming communities in India. These varieties, with traits like enhanced drought tolerance, pest resistance, and improved nutritional profiles, have contributed to increased food security and income for smallholder farmers. In Rajasthan, for instance, the introduction of drought-tolerant pearl millet varieties has enabled farmers to sustain production even in years of low rainfall, thereby providing a measure of economic stability. Additionally, the cultivation of nutritionally enhanced millets has implications for public health, particularly in combating micronutrient deficiencies in rural areas [19].

7. FUTURE PERSPECTIVES

A. Emerging Trends in Millet Research

In India, millet research is rapidly evolving, with new trends shaping the future of millet cultivation and utilization. One significant trend is the increasing focus on the nutritional value of millets, driven by growing health awareness among the population. This has led to enhanced research on biofortified millets, aiming to increase their micronutrient content, particularly iron, zinc, and calcium [20]. Another emerging trend is the integration of millets in food processing and value addition. Research is being directed toward developing millet-based processed foods that are not only nutritious but also cater to changing consumer preferences. This includes the development of millet-based snacks, beverages, and gluten-free products, tapping into the growing market for health foods [21].

B. Potential Areas for Further Exploration

Several areas hold potential for further exploration in millet research in India, which could significantly contribute to agricultural sustainability and nutritional security. The application of genomics and bioinformatics in millet research is gaining momentum. Advanced genomic tools can accelerate the breeding of improved millet varieties with desirable traits such as drought tolerance, pest resistance, and improved nutritional profiles. Genome-wide association studies (GWAS) and genomic selection (GS) are particularly promising in this regard [22]. Given the impact of climate change, there is a growing emphasis on climate-smart agriculture. Millets, with their inherent resilience to adverse climatic conditions, are an ideal focus for developing climate-smart agricultural practices. Research is needed to optimize millet cultivation practices that can mitigate the impacts of climate variability while ensuring high productivity [23]. Nutritional enhancement of millets is another area ripe for exploration. This includes both biofortification and the development of functional foods. Utilizing the genetic diversity of millets to enhance their micronutrient content and exploring their potential health benefits are key research areas that can address malnutrition challenges in India [24].

C. Policy and Funding Considerations for Millet Research

Policy and funding are critical in shaping the future of millet research in India. There is a need for policies that promote the cultivation and consumption of millets, recognizing their role in food security and nutrition. Government support in terms of funding for millet research, especially in areas like genomics, breeding for climate resilience, and nutritional enhancement, is crucial. Additionally, policies that encourage public-private partnerships in millet research can lead to more innovative and effective solutions. Ensuring that the benefits of research reach the farmers, especially in marginalized and drought-prone areas, should be a key consideration in policy formulation and funding allocation [25].

8. CONCLUSION

Exploring the genetic diversity of millets in India offers a multifaceted opportunity to enhance crop resilience, address nutritional deficiencies, and adapt to environmental challenges. The extensive variability within millet species, both intra and inter-specific, underscores the potential for breeding programs to develop improved varieties tailored to diverse ecological and climatic conditions. Challenges such as genetic erosion and access to genetic resources highlight the need for integrated strategies combining traditional knowledge with modern scientific advancements. The success stories and lessons learned from past breeding programs in India demonstrate the significant impact of improved millet varieties on farming communities, contributing to sustainable agriculture and food security. Looking ahead, emerging trends in research, potential areas for exploration, and policy considerations set the stage for innovative approaches in millet cultivation, ensuring their role as a crucial crop in the future of Indian agriculture.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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