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From Neglected to Mainstream: High-Throughput Phenotyping and the Modernization of Millet Breeding

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Millets, once considered "orphan crops," are now emerging as vital components of climate-resilient agriculture and global food security. Despite their inherent advantages—such as drought tolerance, nutritional richness, and adaptability to marginal environments. The advent of high-throughput phenotyping (HTP) marks a turning point in millet breeding by enabling rapid, precise, and large-scale assessment of plant traits. This article explores the transition of millets from neglected crops to mainstream agricultural commodities, focusing on how HTP technologies—integrating imaging, sensors, artificial intelligence, and genomics—are revolutionizing breeding strategies. It highlights current advancements, challenges, and future prospects, positioning HTP as a cornerstone of next-generation millet improvement programs.

Rediscovering Millets in a Changing World

For centuries, millets such as pearl millet, finger millet, and foxtail millet have sustained populations in arid and semi-arid regions. Yet, during the Green Revolution, global agricultural priorities shifted toward rice and wheat, relegating millets to the margins of research and policy. Today, this narrative is rapidly changing. Climate change, water scarcity, and nutritional insecurity have renewed interest in millets. Their resilience to drought, poor soils, and high temperatures makes them ideal for sustainable agriculture. Moreover, millets are rich in micronutrients, fiber, and bioactive compounds, making them "smart foods" for the future. However, unlocking the full potential of millets requires modern breeding approaches—and this is where high-throughput phenotyping becomes transformative.

The Phenotyping Bottleneck in Millet Breeding

Traditionally, breeding a better millet variety was a painstaking, manual process. A breeder would walk through thousands of rows of plants, clipboard in hand, estimating plant height, counting tillers, or judging the "stay-green" quality of leaves by eye. This "phenotyping"—the measuring of physical traits—was the slowest part of the breeding cycle.

While genomic sequencing (mapping the DNA) has become incredibly fast and cheap, our ability to measure how those genes actually perform in the field lagged behind. This created a phenotyping bottleneck. We had the genetic blueprints, but we couldn't accurately or quickly see which plants were truly winning the race against drought or nutrient deficiency.

Plant breeding relies on two pillars:

- **Genotyping** (understanding DNA variation)
- **Phenotyping** (measuring observable traits)

While genotyping has advanced rapidly with next-generation sequencing, phenotyping has remained a bottleneck. Traditional methods involve manual measurements of plant height, biomass, or yield components—processes that are:

- Labor-intensive
- Time-consuming
- Prone to human error
- Limited in scale

In millets, which often exhibit high genetic diversity and complex trait interactions, these limitations are even more pronounced. Recent research on foxtail millet highlights that manual phenotyping is inefficient and inaccurate, hindering the evaluation of genotypic variation and slowing breeding progress.

What is High-Throughput Phenotyping (HTP)?

High-throughput phenotyping refers to the use of **automated, sensor-based technologies** to measure plant traits rapidly, accurately, and at scale.

1. Aerial Phenotyping: The Drone Vanguard

Unmanned Aerial Vehicles (UAVs) equipped with multispectral and thermal cameras now fly over millet nurseries. They can calculate the **Normalized Difference Vegetation Index (NDVI)**—a measure of plant health—for thousands of plots in minutes. Thermal sensors detect "canopy temperature," a critical indicator of how well a millet plant is managing water under heat stress.

2. Ground-Based Robots and "Pheno-mobiles"

In the field, sensor-laden vehicles (pheno-mobiles) crawl between rows, using **LiDAR (Light Detection and Ranging)** to create 3D models of the plants. This allows breeders to measure biomass and architectural traits, such as leaf angle, which determines how efficiently the plant captures sunlight.

3. Digging Deeper: Root Phenotyping

Millets are famous for their "deep-searching" roots, but studying them used to mean digging the plant up—effectively killing it. Modern HTP uses **rhizotrons** (transparent soil observations) and even **X-ray Computed Tomography (CT)** to visualize root architecture in real-time without disturbing the plant.

HTP allows researchers to monitor thousands of plants simultaneously under different environmental conditions, generating massive datasets for analysis.

According to recent studies, HTP enables **precise measurement of traits across large populations**, accelerating the selection of superior genotypes for yield, stress tolerance, and quality .

High-Throughput Phenotyping in Millet: Recent Advances

Imaging-Based Phenotyping Systems

A landmark development in millet research is the use of **high-throughput imaging systems (HIS)**. These systems capture plant images at multiple angles and time points to extract traits such as:

- Plant height
- Leaf area
- Biomass proxies
- Growth dynamics

In foxtail millet, HIS has demonstrated the ability to extract key parameters like convex hull area and side projected area with high precision.

Integration with Genomics

One of the most powerful aspects of HTP is its integration with genomic tools such as **Genome-Wide Association Studies (GWAS)**.

By linking phenotypic data with genetic markers, researchers can:

- Identify genes controlling important traits
- Understand physiological mechanisms

- Accelerate marker-assisted selection

For example, HTP combined with GWAS in millet has identified genetic loci associated with plant height and linked them to **gibberellic acid pathways**, crucial for growth regulation .

Field-Based Phenotyping

Modern HTP is not confined to controlled environments. Field-based platforms using drones and mobile sensors enable real-time monitoring under natural conditions, capturing traits such as:

- Drought response
- Canopy temperature
- Nutrient status
- Disease progression

This is particularly important for millets, which are often grown in stress-prone environments.

From "Minor" to "Mainstream": Why Now?

The transition of millets to the mainstream isn't just about technology; it's about a global shift in priorities:

- **Climate Resilience:** Millets can grow in temperatures exceeding **42°C** and require a fraction of the water needed for rice. HTP helps breeders perfect these traits for "worst-case" climate scenarios.
- **Nutritional Security:** Dubbed "Super Cereals," millets are rich in iron, zinc, and calcium. HTP allows breeders to select for "biofortified" varieties to combat hidden hunger.
- **Economic Viability:** By reducing the time to release a new variety from 12 years to just 6 or 7, HTP makes millet farming more profitable for large-scale producers.

Challenges in Implementing HTP for Millets

Despite its promise, several challenges remain:

High Initial Investment

HTP platforms require expensive infrastructure, including sensors, drones, and data processing systems.

Data Management and Analysis

HTP generates massive datasets requiring advanced computational tools and expertise in data science and bioinformatics.

Standardization Issues

Lack of standardized protocols for data collection and analysis can limit comparability across studies.

Limited Adoption in Developing Regions

Many millet-growing regions lack access to advanced technologies, slowing the adoption of HTP.

The Role of Artificial Intelligence and Digital Agriculture

The future of millet phenotyping lies in the integration of **AI and machine learning**. These technologies can:

- Automate trait extraction from images
- Predict plant performance
- Optimize breeding decisions

Emerging platforms even allow smartphone-based phenotyping, democratizing access to advanced tools and reducing costs.

Millets in the Mainstream: Policy and Global Momentum

The global recognition of millets has gained momentum, highlighted by initiatives such as the **International Year of Millets (2023)**. Governments and research institutions are increasingly investing in:

- Millet genomics

- Digital agriculture
- Climate-smart breeding

HTP is central to these efforts, bridging the gap between traditional knowledge and modern science.

Case Study: Pearl Millet and the Fight Against Heat

Research conducted at institutes like the **International Crops Research Institute for the Semi-Arid Tropics (ICRISAT)** and the **ICAR-Indian Institute of Millets Research (IIMR)** has shown the power of HTP in action. In recent 2024 and 2025 trials, large-scale nurseries of pearl millet inbreds used HTP to identify genotypes with superior "transpiration efficiency." By integrating HTP data with **Machine Learning (ML)**, scientists can now predict grain yield months before harvest. For example, Support Vector Machines (SVM) and Random Forest (RF) algorithms can analyze hyperspectral data to detect nitrogen deficiency or early-stage fungal infections (like blast or downy mildew) before the symptoms are even visible to a human breeder.

"HTP allows us to move from observing a single point in time to watching a plant's entire life story through data." — Perspective from the 2026 Millet Technology Workshop.

Future Prospects: Towards Precision Millet Breeding

The next phase of millet breeding will likely involve:

- Integration of **phenomics, genomics, and enviromics**
- Development of low-cost, portable phenotyping tools
- Real-time decision support systems for breeders
- Participatory breeding using digital platforms

Ultimately, the goal is to create **precision breeding pipelines** that can rapidly deliver high-yielding, nutritious, and climate-resilient millet varieties.

Conclusion

Millets are no longer “neglected crops.” They are at the forefront of sustainable agriculture and nutritional security. High-throughput phenotyping has emerged as a game-changing technology, transforming how these crops are studied, improved, and deployed. By overcoming the phenotyping bottleneck, HTP enables faster, smarter, and more precise breeding. As technologies become more accessible and integrated with artificial intelligence, millet breeding is poised to enter a new era—one where data-driven innovation ensures resilience, productivity, and sustainability.

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