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Original article**Leveraging High Throughput Phenotyping for physiology-driven crop improvement****Priyanka Negi¹***¹Ph.D. scholar, Post Graduate Institute, Mahatma Phule Krishi Vidyapeeth, Rahuri, and ICAR-NIASM (National Institute of Abiotic Stress Management), Baramati, Maharashtra***Corresponding author: priyankanegi15119@gmail.com**Received: 26/10/2025**Published: 01/11/2025***ABSTRACT**

Crop phenotyping involves analysing plant traits to identify the key characteristics that contribute to higher yield, productivity, and improved tolerance to stress conditions. Knowledge gained from High-Throughput Phenotyping (HTP) plays a crucial role in screening and selecting favourable genotypes for breeding programs. HTP platforms, which leverage modern digital tools, advanced techniques, and specialized software, have significantly simplified this process. Although traditional HTP methods have been expensive, researchers worldwide are developing more affordable solutions using cost-effective tools, cameras, sensors, and open-access software, making these technologies more widely accessible. By linking genomics with real-world field performance, HTP bridges the gap between a plant's genetic potential and its actual agricultural outcomes. While genomic research has advanced rapidly, phenotyping continues to evolve, gradually overcoming its historical role as a bottleneck in crop improvement programs.

Keywords: High-Throughput Phenotyping, Stress adoptive traits, Affordable Phenotyping, Digital agricultural tools

INTRODUCTION

Phenotyping refers to the study of an organism's observable traits, which result from the interaction between its genetic makeup and the surrounding environment. In plants, phenotyping involves examining various morphological, physiological, biochemical, and molecular characteristics. It plays a vital role in crop improvement, as identifying and selecting the most desirable phenotypes is a crucial first step in plant breeding and agricultural advancement. With climate change intensifying alongside population growth and limited natural resources, the need for efficient crop selection has become more urgent. Traditionally, recording key agricultural traits—such as yield, nutritional quality, and stress tolerance—has been a laborious and time-consuming process. However, the emergence of HTP technologies has transformed this field by enabling rapid and large-scale screening of plant traits that contribute to higher yield and productivity.

Concept of High-Throughput Phenotyping

HTP refers to the automated, rapid, and large-scale assessment of plant traits. This advanced technology has transformed traditional phenotyping by incorporating imaging and sensor-based methods, enabling faster and more precise measurement of plant characteristics. HTP systems use automated sensing, data collection, and analytical tools to generate comprehensive phenotypic data efficiently. Through this approach, plants can be evaluated for desirable traits across different growth stages, enhancing the precision of crop screening.

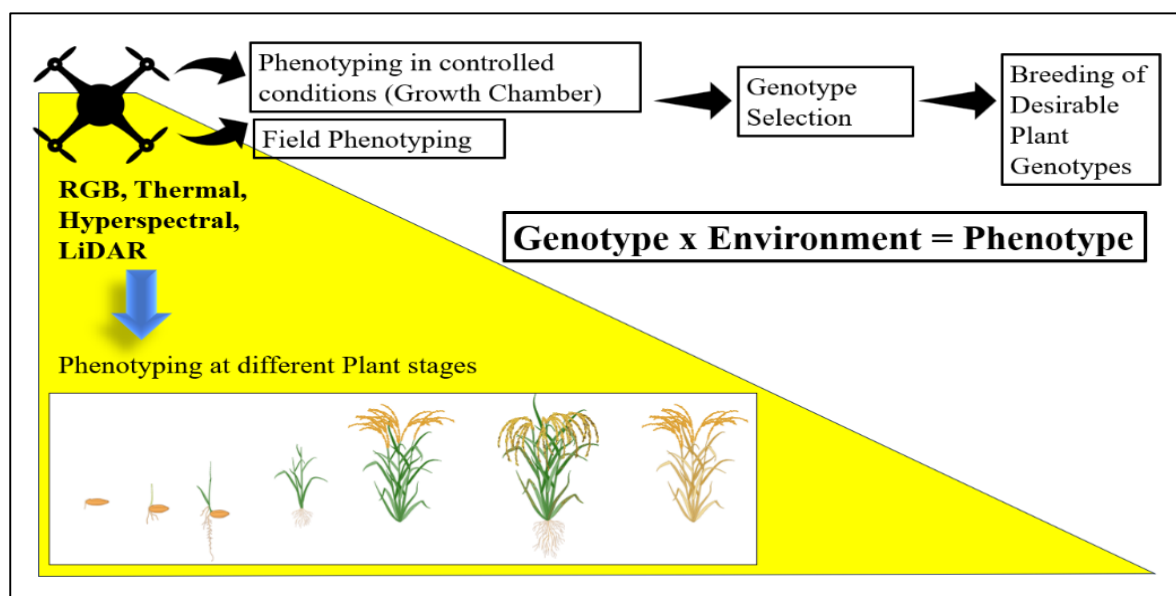


Figure 1. Comprehensive Overview of key applications in High-Throughput Phenotyping (HTP).

Depending on where the process is carried out, phenotyping can be classified into two main types: field phenotyping, which utilizes drones and unmanned aerial vehicles (UAVs), and controlled-environment phenotyping, which takes place in greenhouses or growth chambers (Fig. 1.). Because HTP primarily uses imaging technologies, it allows non-destructive and real-time monitoring of key physiological parameters such as canopy temperature, chlorophyll fluorescence, and other growth-related traits throughout the plant's development. These measurements are made possible through the integration of various digital tools, sensors, and analytical software. Ultimately, since a phenotype arises from the interaction between genotype and environment, the data collected through HTP enable researchers to identify and select the best-performing genotypes for breeding programs aimed at developing superior crop varieties with desirable traits (Fig.1.).

Physiological Traits in Focus

HTP serves as a physiological tool for evaluating functional traits that influence crop performance. It focuses on measurable physiological parameters that reflect a plant's health, efficiency, and productivity. For instance, canopy temperature is used to assess transpiration efficiency, which is directly related to drought tolerance; chlorophyll fluorescence helps determine the efficiency of photosystem II (PS II) and overall quantum yield; while measurements of growth rate and leaf area at specific growth stages provide insights into biomass accumulation and yield potential. By

analysing these physiological indicators, HTP enables plant breeders to efficiently screen and identify genotypes with desirable traits, thereby accelerating the achievement of crop breeding goals and contributing to overall crop improvement. Some majorly used important physiological traits and the sensors associated with them are shown in the table 1.

Physiological Trait	Sensor	Breeding relevance
Crop Morphology	Visible (RGB) Camera	Helps in selection of crop ideotypes
Tissue water content	Near-Infrared (NIR) Camera	Used for screening drought adaptive traits
Canopy Temperature	Infrared/Thermal (IR) Camera	Used for screening genotypes having cooler canopies
Chlorophyll Fluorescence	PAM (Pulse-Amplitude-Modulation) Fluorometer	Helps in screening of stress tolerant lines
Greenness/Chlorophyll	SPAD (Soil Plant Analysis Development)	Helps in screening of nitrogen efficient genotypes

Table1: Key Physiological Traits and Sensor Technologies Utilized for Genotypic Screening in Crop Breeding.

Technological innovations driving High-Throughput Phenotyping

A wide range of imaging technologies—such as RGB, thermal, multispectral, and hyperspectral imaging—are now integral components of HTP systems used in advanced phenomics facilities. These imaging tools enable precise measurement of multiple physiological and morphological traits, including leaf area, tissue water content, plant structure, and overall growth characteristics. In recent years, innovative platforms have been developed worldwide to make imaging more efficient and accessible. These include ground-based systems like phytotron facilities, aerial platforms such as drones and unmanned aerial vehicles (UAVs), and space-based systems utilizing satellites for large-scale crop monitoring. To manage and analyse the massive amounts of data generated from these imaging systems, researchers increasingly rely on Artificial Intelligence (AI), Machine Learning (ML), and specialized image analysis software such as *ImageJ*, *Petiole Pro*, and *PlantCV*.

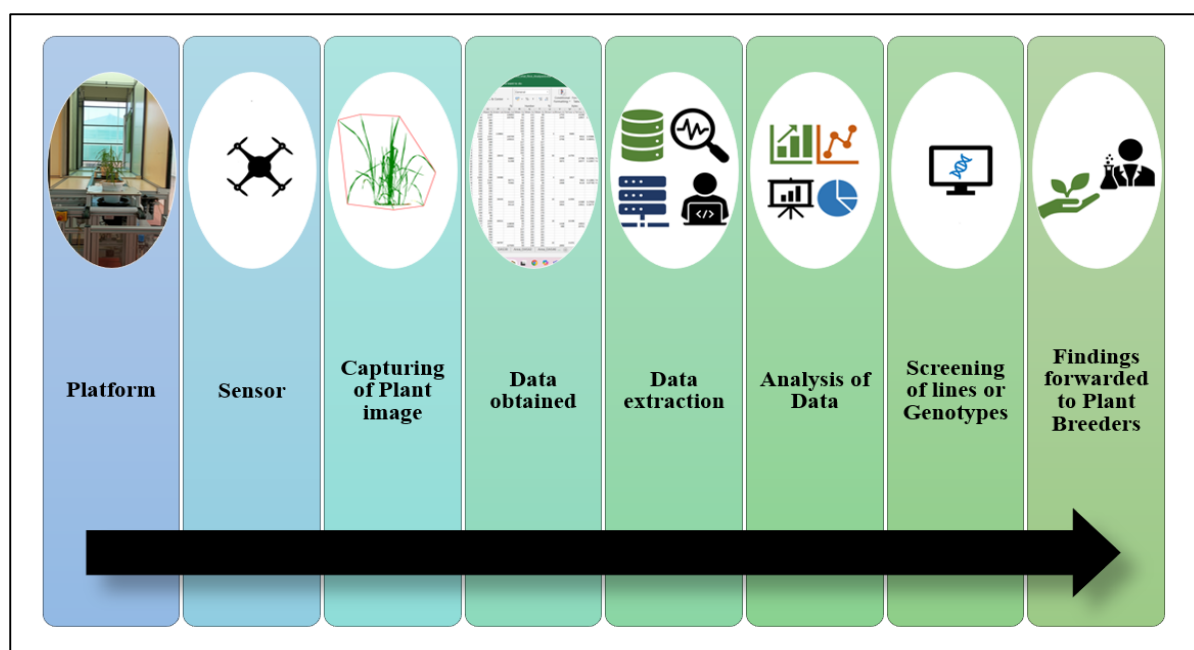


Figure 2. Schematic Representation of HTP (High-Throughput Phenotyping) Workflow.

An accurate schematic representation of the HTP workflow, incorporating modern tools and techniques, utilising proper software for analysis of recorded data (Fig.2.), can significantly contribute to achieving the Sustainable Development Goals (SDGs) and facilitate the efficient development of crop genotypes with superior performance and enhanced stress tolerance. Additionally, the Internet of Things (IoT) plays a key role in facilitating real-time data collection and cloud-based processing, enabling faster and more accurate generation of actionable insights for crop improvement and management.

Applications in Crop Improvement

Many crops of cultural, regional, and economic significance—such as rice, millets, wheat, sorghum, and pulses—are extensively studied worldwide to understand the physiological traits that enable them to thrive under unfavourable or stress conditions like heat, salinity, drought, or limited water availability. The process generally involves screening different genotypes of a target crop to identify those with desirable traits, followed by breeding them with other superior genotypes to develop high-performing, stress-tolerant, and disease-resistant varieties or cultivars. The major applications of HTP in crop improvement include:

- ✚ Screening genotypes for early seedling vigour
- ✚ Predicting yield potential
- ✚ Phenotyping for stress tolerance traits such as drought, salinity, and heat resistance
- ✚ Detecting plant diseases through hyperspectral imaging at various growth stages
- ✚ Screening genotypes for Nutrient Use Efficiency (NUE)

Several renowned research institutions have successfully implemented HTP technologies in their crop improvement programs. For example:

- ✚ The International Maize and Wheat Improvement Centre (CIMMYT) in Mexico utilizes HTP platforms for wheat phenotyping.

- ✚ The International Rice Research Institute (IRRI) employs drone-based phenotyping for rice research, enabling scientists to collect precise and large-scale data for improving rice varieties.

Challenges and Future Prospects

Traditionally, HTP has been an expensive technology, making its large-scale implementation feasible mainly in developed countries. This high cost has limited accessibility for many researchers and institutions wishing to benefit from its potential. Additionally, the vast amount of data generated through HTP can be challenging to analyse, requiring advanced analytical tools, specialized software, and skilled expertise. Looking ahead, the future of plant research should focus on making HTP technologies more affordable and cost-effective, ensuring that they are accessible to researchers worldwide. Expanding these facilities beyond developed nations would promote high-quality research and contribute to global sustainable agricultural development.

Did you know?

At present, India has only four major HTP or phenomics facilities, strategically located across different states. These centres play a crucial role in advancing plant research and breeding by enabling precise, large-scale phenotypic analysis under various environmental conditions. The key HTP facilities in India include:

- ✚ Nanaji Deshmukh Plant Phenomics Centre, ICAR-IARI (Indian Agricultural Research Institute), New Delhi
- ✚ Plant Phenomics National Facility (PPNF), ICAR-IIHR (Indian Institute of Horticultural Research), Bengaluru, Karnataka
- ✚ Plant Phenomics Facility, ICAR-NIASM (National Institute of Abiotic Stress Management), Baramati (Malegaon), Maharashtra
- ✚ Plant Phenomics / High-Throughput Phenotyping Facility, ICAR-CRIDA (Central Research Institute for Dryland Agriculture), Hyderabad, Telangana

These facilities represent significant milestones in India's journey toward data-driven, climate-smart agriculture, supporting the development of improved and resilient crop varieties.

Phenomics-assisted plant breeding represents a vital step toward developing superior genotypes with enhanced traits that are available to all, regardless of social or economic background. To achieve this, researchers are increasingly exploring low-cost, image-based phenotyping approaches that can be easily adopted. In particular, mobile- and tablet-based phenotyping applications are emerging as practical and accessible tools, offering real-time data collection and analysis. These app-based solutions are not only the future direction of plant phenotyping but also a current necessity for ensuring equitable progress in crop improvement research.

CONCLUSION

HTP provides a deeper physiological understanding of crop performance, making it a transformative tool in advancing modern crop breeding. By effectively linking plant function with genetic information, HTP serves as a bridge between genomic insights and real-world field performance, representing a new frontier in agricultural science. Through image-based and non-destructive analysis, HTP enables precise, real-time monitoring of plant traits without harming the crop. This approach empowers researchers to identify and select resilient varieties more efficiently, ultimately contributing to the development of sustainable, climate-resilient agricultural systems capable of meeting the growing global food demands.

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