Available online at
http://agrospheresmagazine.vitalbiotech.org/

ISSN (E): 2582 – 7022

Agrospheres:e- Newsletter, (2026) *7*(5), 133-140

Article ID: 989

Plant Phenomics: Bridging Genetics, Environment and Crop Performance

Sajan Kumar[1], Abhishek Kumar[2], Rakesh Kumar[1], Ashutosh Sharma[1], Ashutosh Singh[1]

[1]RLB Central Agricultural University, Jhansi, U.P., India
[2]Bihar Agricultural University, Sabour, Bhagalpur, Bihar

Open Access

*Corresponding Author
Ashutosh Singh*

Article History
Received: 15.05.2026
Revised : 20.05.2026
Accepted: 25.05.2026

INTRODUCTION

Global crop productivity depends on the interaction between genetic composition of the plants and environmental conditions in which they grow. The conventional plant breeding and conventional has primarily depends on the visual observation and manual measurement of the plant phenotypic traits. The traditional approaches of phenotypic evaluation and interpretation of traits have significantly contributed to crop improvement strategy. The manual approaches of data observation are often time-consuming, labor-intensive and unable for maintaining large scale breeding populations. The visual observation of phenotypic characters of some important traits at various developmental stages of the plants is unable to characterize due to lack of proper characterization guidelines in many crops.

Recent advancement in the genomic science and technology enable to sequence the whole plant genome precisely and economically. Translation of genomic information or date into improved crop performance facing challenges due to lack of similarly developed rapid phenotyping methods. Such challenges are referred as phenotyping bottleneck (Amin, et al., 2025). The plant phenomic play crucial role in addressing said bottleneck through imaging techniques, robotics, sensors and advanced computational tools to collect and huge morphological data. Plant phenomics also strengthen the proper characterization of plant developmental stage, plant growth, and physiological response of the plants under stressed situation. Further, plant phenomics provide strength to creation of relationship among the genes/traits, environmental conditions and crop performance (Cobb, et al., 2013).

2. Plant Phenomics

Term phenomics is derived from word phenotype which encompasses among the observable morphological parameters including plant height, biomass, flowering duration, fruit/grain characteristics, leaf area, shoot and root architecture, photosynthetic efficiency, disease tolerance, and yield attributing traits. Plant phenomics is the proper and strategic study of the scaling of phenotypic data on brad spectrum using high-throughput and automated technology. The major objective of plant phenomics to quantify the plant traits under diverse range of climatic condition and development of relationship among the observation recorded with available genetic information (Hrzich, et al., 2025). Plant phenomics may further enables to comprehensive analysis of the major phenotypic traits at different plant growth stages under diverse range of environmental conditions.

3. Plant phenotypes

Plant phenotypes are the characteristics of the plant observed during evaluation. Most of the observable characteristics are resulting from its genes influenced by environment. Plant phenomic approaches have ability to track these traits across the scales related to plant morphology, physiological, biochemical and phenological parameters of the plant (Li, et al., 2021). Traits tracks across the multiple scales are:

3.1. Morphological: Morphological traits of any plant include plant height, leaf area index, plant canopy, architecture, biomass and root system.

3.2. Physiological and Biochemical Traits: Major physiological and biochemical traits of the plants are stomatal conductance, transpiration, water absorption, water use efficiency, photosynthetic efficiency and photosynthetic pigments including chlorophyll contents.

3.3. Phenological characteristics: The phenological traits of plants studied under plant phenomics are various growth stages of the plant, flower initiation, flowering time, canopy senescence and yield attributing components.

4. Technology driving plant phenomics

Plants phenomics are completely depends on the technology and highly useful for the rapid observation of plant characteristics. The plant phenomics is accelerated by cutting-edge hardware and automated workflow platform able to large scale data collection from manual to automated digital pipelines (Brichet, et al., 2017). There is several technology driving approaches of plant phenomics useful in the big-data collection using phenotypic expression of the plants under diverse environmental condition.

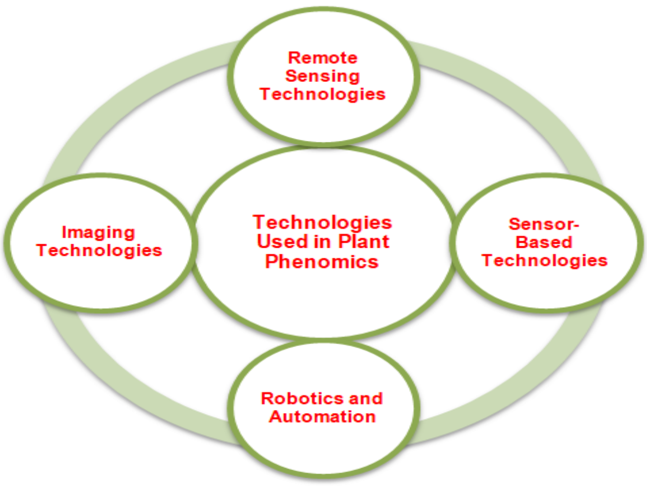

Fig.1: Various technologies used in plant phenomics.

ISSN (E): 2582 – 7022

4.1. Advanced Imaging Modalities

Advanced imaging modalities enable non-destructive, high-throughput monitoring of plant traits using technologies such as RGB, hyperspectral, multispectral imaging, thermal, fluorescence, chlorophyll imaging etc. These methods capture structural, physiological, and biochemical information, facilitating precise assessment of growth, stress responses, health, and productivity.

4.1.1. RGB Imaging: RBG imaging is the red, green and blue automated imagination system installed with high resolution digital cameras. The RGB imagination system works on the principle of additive colour mixing (Roitsch, et al., 2019). The high resolution installed in the system has ability to adjust the intensity of blue, green and red light for each pixel. These high-resolution cameras have ability to capture structural traits of the plant such as growth rates, colour diversity and digital biomass.

4.1.2. Multispectral and Hyperspectral Imaging: Multispectral and hyperspectral imagination system is employed in the plant monitoring for large scale data collection. This is one of the advanced remote sensing technologies able to analyze how plants reflect various wavelengths of light. The sensor inbuilt in the system evaluates subtle variability in the plant pigment, water status, chemical constituents, and stage before it is visible to the human (Roitsch, et al., 2019). It is highly useful in the early stage of stress detection in various environmental conditions.

Table-1: Spectral changes in multispectral and hyperspectral imaging for various types of stresses.

Stress type	Spectral changes
Drought/Water deficit condition	Reduced SWIR absorption, altered NIR reflectance
Nitrogen deficiency	Lower chlorophyll-related absorption in red wavelengths
Disease infection	Changes in pigment composition and cellular structure
Heat/high temperature stress	Altered reflectance in red-edge and NIR regions
Salt stress	Shifts in water and pigment-related spectral feature

4.1.3. Thermal Infrared Imaging: Thermal infrared (TIR) imaging is one of the powerful non-destructive systems highly useful for proper monitoring of the plant physiological responses like water status and drought stress (Mahlein, et al., 2012). It is also useful in the canopy temperature monitoring for water loss from the aerial organs of the plants via transpiration and guttation, stomatal conductance, water uptake by plant under water deficit condition. Beyond drought assessment, it is also useful in the physiological disturbances associated with nutrient deficiency, salinity stress, and heat stress.

4.1.4. Chlorophyll Fluorescence Imaging: This is one of the advanced optical sensing technologies employed for real-time assessment of photosynthetic performance. The chlorophyll fluorescence imaging provides direct insights into the functioning of photosynthetic apparatus (Photosystem II).

4.2. Field and Controlled Platforms

The field and controlled platform in plant phenomics includes controlled environmental systems like greenhouses, Phytotrons, field-based phenotyping platform (FPPs), AI, machine learning etc.

4.2.1. Controlled-Environment Platforms (Greenhouses/Phytotrons): Phytotrons and greenhouses are highly relegated controlled environmental platform suitable for plant genetic research and phenotyping. The fully automated Phytotrons are enabled to high-throughput non-destructive monitoring of the plant phenotype such as growth, morphology, physiological and stress responses. In greenhouses and phytotron facility environmental variables like humidity, light, temperature, photoperiod, irrigation and carbon dioxide concentration are precisely controlled. Controlled conditions inside the platform may minimize environmental noises and allow researchers to quantify genetic effect on the plant traits with significant accuracy and high reproducibility.

4.2.2. Field-Based Phenotyping Platforms (FPPs): Field-based phenotyping platforms are useful for the large-scale assessment of the plant traits under suitable conditions. The FPPs platform display accurate and high level of data collection of the phenotypic traits. The automated sensors inbuilt in the FPPs system collects high-resolution spatial temporal data on the plant growth, physiological parameters, stress responses and yield attributing characteristics. Further, FPPs system may also enable to evaluate the plant behavior under complex interaction among genetic and management practices in the fluctuating environmental conditions like temperature, humidity, rainfall, soil condition and biotic stresses (Lozano-Claros, et al., 2020). Thus, FPPs facilities are more reliable to understand the genotypic performance and adaptation across agroecological situations.

4.3. The Data Revolution: AI and Machine Learning

The data generation in plant phenomics is driven by artificial intelligence (AI) and machine learning (ML), which can be properly analyze by high-throughput technologies. The prediction of morphological traits, disease mechanism and rainfall pattern etc. can be identified by advanced computational pipelines. The AI and ML tool are able to transform big raw data into actionable insights and accelerates plant breeding programs.

4.3.1. Computer Vision (CV): The computer visions (CV) are automated device inbuilt with advanced software capable to analyze plant images by identifying the plant organs like leaves, stems, frits, grains, seeds etc. The computer vision increases the data collection and analysis, reduces manual efforts and supports crop improvement research.

4.3.2. Deep Learning (DL): Deep learning (DL) in plant phenomics accelerates detection of diseases, insects – pests damage and nutrient deficiency using imaging data. It I also enable to automatically learn complex visual pattern in support of large-scale phenotyping, disease detection at early stage to accelerate crop breeding programs and precision agriculture.

4.3.3. Predictive Modeling (PM): Predictive modeling uses machine learning to integrate historical phenotypic records under variable environmental conditions like high-low temperature, unpredictable rainfall, diverse soil nutritional status etc. These models also enable the forecasting of plant growth, crop yield and biomass before harvesting to accelerate crop breeding strategies for sustainable agricultural development and crop improvement.

5. Applications in Modern Agriculture

Plant phenomics plays important role in the precision farming and modern agriculture by enhancing high-throughput interpretation of plant traits with the help of imaging system, advanced sensors and data analytics. Plant phenomic approaches speedup plant breeding in terms of stress tolerance evaluation, screening for disease infection, prediction of yield and resource standardization. Further, interconnecting the plant phenotypic data with environmental factors and genetic makeup of the plants enhance the development of resilience for development of sustainable crop cultivars (Araus and Kefauver, 2018).

ISSN (E): 2582 – 7022

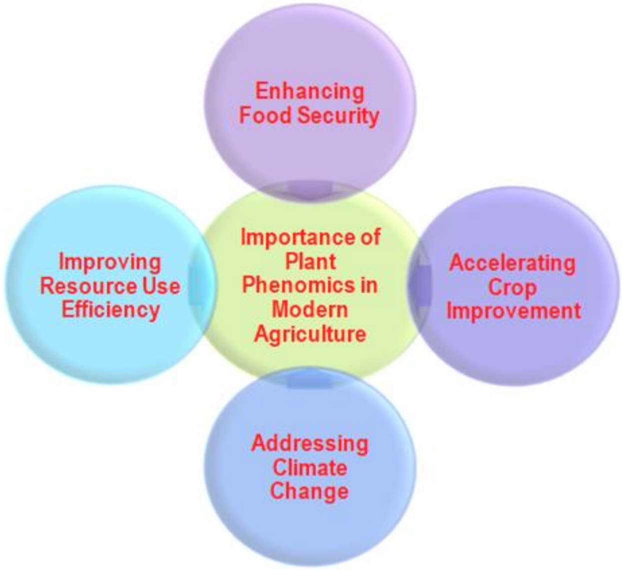

Fig.2: Importance and application of phenomics in precision and modern agriculture**.**

5.1. Accelerating Crop Breeding

High-throughput phenotyping gives precise data that enhances genome-wide association studies (GWAS), genomic selection (GS). Thus, integration of datasets with genomic data accelerates perdition of accuracy generated for most of the complex phenotypic traits.

5.2. Precision Stress Phenotyping

Stress phenotyping is difficult to access due to huge variability in the environmental conditions. The plant phenomics base precision stress phenotyping enables rapid and accurate assessment of plant responses to the environmental stress like drought, heat and waterlogging. Thus, precision stress phenotyping strengthens the plant phenotyping by tackling the critical observation of abiotic threats such as water deficit, high wind velocity and heat waves (Bethge, et al., 2023). The well-equipped and automated sensor technologies properly monitor traits contributing drought, heat, salinity and nutrient deficiency may facilitate researchers to screen genotypes that maintain canopies, efficient water use and deeper root system for optimizing the uptake of water and essential nutrients under unfavourable environmental conditions. Moreover, plant phenomics based analysis of growth and physiological responses also enables to screen stress-tolerant crop cultivars for minimizing ion toxicity and enhancing nutrient use efficiency.

5.3. Transforming Precision Agronomy

Plant phenomics is one of the important branches of omic science bridging the gap between science and agriculture through development of sensor technologies in the global farming systems. The sensor-based studies particularly developed for phenotyping research would support of precision agronomical practices by data-driven management practices. Plant phenomic facilities may efficiently strengthen the proper rate of nitrogen application, irrigation scheduling based on crop canopy temperature and crop water status. For strategic controlling of insects and pests, plant phenomics also facilitates targeted pesticide and chemical treatment at early stage of the infection. Furthermore, fully-automated plant phenomic facility optimizes the resource use and reduces unnecessary inputs. Thus, plant phenomics based precision agriculture enhances productivity, reduces operation costs and minimizes diverse environmental impacts directly contributing to the agricultural sustainability in the present scenario of climate change.

6. Key Challenges and Bottlenecks

Rapid technological advancement to impart the crop improvement program strengthens crop evaluation at phenotypic and genetic level for the development of crop cultivars suitable for diverse environmental condition. Plant phenomics is one of important approach for evaluation and high-throughput data collection and interpretation to accelerate crop breeding for global agricultural sustainability. The widespread adaptation of phenomics faces numerous challenges due to high cost of phenomic infrastructure development, sophisticated facilities like automated Phytotrons and greenhouses, robotic platform, hyperspectral imaging systems etc. Furthermore, the plant phenomic technologies are restricted due to lack of well-granted research institutions and large agricultural corporations (Yang, et al., 2020). Additionally, the plant phenomic platform produces high-throughput imaging and sensor date required broad storage system, high-performance computing system and learned bioinformatics professionals for strategic analysis and management. Due to lack of these facilities, the field of plant phenomics faces the lack of standardized data collection and metadata protocol. Furthermore, the differences in the measurement methods, platform design and diverse environmental conditions make it difficult to compare and integrate datasets across the growing seasons and particular locations. Therefore, addressing such type of challenges is more essential for maximizing the impact of plant phenomics at global level.

7. Future Prospects

Plant phenomics enables to generate high-throughput data generation and analysis of plant traits under diverse environmental condition. Technological advancement including artificial intelligence, robotics, machine learning, sensor technologies may accelerate the phenotypic data collections and development of relationship among the morphological characters and yield attributing traits. Further integration of plant phenomic data with genomics and transcriptomics and metabolomics may enhance the understanding of complex genotype-phenotype relationship to accelerate crop breeding strategies (Anand, et al., 2026). Emerging approaches and modernization in plant phenomics like field robots, drones, digital twins and real-time monitoring systems will support the future precision agriculture and sustainable crop management in the era of climate change. In future, plant phenomics will display crucial role in the development of high-yielding, climate-resilient crop cultivars withstand with high temperature, heat, salinity and pests.

7.1. Multi-Omics Integration: Integration of plant phenomics with multi-layer omics display holistic understanding between genomics, transcriptomics, proteomics, and metabolomics. The future of plant research lies in the seamless integration of entire omics for agricultural sustainability (Wu, et al., 2024).

7.2. Digital Twins and Predictive Agriculture: The digital twins the transformative advancement in omics enables to create virtual, AI-driven replicas of the real-world crops. The digital twin's model may continuously accelerate and integrate the real-time data from drones, sensors and field-based phenotyping to accurately mirror the growth dynamics of individual plants including crop systems. Digital twin system can also contribute to the researchers for evaluation of the effect of drought, heat, salinity, nutrient availability without conducting lengthy field trials.

7.3. Fully Autonomous Field Ecosystems: The next-generation of agricultural research and crop management can be achieved by fully automated ecosystem. Integration of advanced plant phenomic approaches like artificial intelligence, robotics, edge computing may accelerate plant trait data generation and integration with genomics, transcriptomics,

ISSN (E): 2582 – 7022

proteomics and metabolomics. Particularly in fully automated field ecosystem, the digital network of permanent ground sensors continuously collect data on soil conditions, crop growth, micro climate and stress responses. The AI-powered cameras in fully automated ecosystem provide real-time monitoring of the plant health and stress response (Stegemann, et al., 2024). Further, edge-computing technologies in the system may enables to accelerate data processing efficiently. The fully automated field ecosystem reduces labors in the date collection, optimize resource utility and enhance productivity. In future, the fully automated field ecosystem would helpful to revolutionize agricultural research, large scale food production and precision forming in the era of climate change.

CONCLUSION

Plant phenomics has emerged as modern discipline of omic science that interlinks the genotypes with observable performance in variable environments. The modern approaches including sensor technologies, robotics, artificial intelligence and advanced imaging enables high-throughput measurement of plant traits at unprecedented precision. The data-driven plant phenomics accelerates crop improvement and enhances the understanding of plant responses into diverse environmental stresses. Further integration of phenomic data with genomic, environmental copes speedup the development o resilient crop cultivars. Therefore, integration of plant phenomics in plant breeding program is highly useful for tackling food security by advancing precision farming, sustainable crop production for the future generations of the world.

REFERENCES

Amin, A., Zaman, W., Park, S. (2025). Harnessing multi-omics and predictive modeling for climate-resilient crop breeding: from genomes to fields. *Genes*16, 809.

Anand, S., Reddy, S.B., Shajini, N., Jose, E., Shirsat, M., Visakh, R.L., Jha, U., Sah, R.P., Beena, R. (2026). Bridging scales: integrated multi-omics and deep phenotyping for climate resilience in crop plants. Front. Plant Sci. 17:1777294.

Araus, J.L. and Kefauver, S.C. (2018). Translating high-throughput phenotyping into genetic gain. *Trends Plant Sci*23, 451–466.

Bethge, H., Winkelmann, T., Ludeke, P., Rath, T. (2023). Low-cost and automated phenotyping system "Phenomenon" for multi-sensor in situ monitoring in plant *in vitro* culture. *Plant Methods*19, 42.

Brichet, N., Fournier, C., Turc, O., Strauss, O., Artzet, S., Pradal, C. (2017). A robot-assisted imaging pipeline for tracking the growths of maize ear and silks in a high-throughput phenotyping platform. *Plant Methods*13, 96.

Cobb, J.N., DeClerck, G., Greenberg, A., Clark, R., McCouch, S. (2013). Next-generation phenotyping: requirements and strategies for enhancing our understanding of genotype–phenotype relationships and its relevance to crop improvement. *Theor. Appl. Genet*126, 867–887.

Hrzich, J., Beck, M.A., Bidinosti, C.P., Henry, C.J., Manawasinghe, K., Tanino, K. (2025). A low-cost photogrammetry system for 3D plant modeling and phenotyping. *arXiv preprint*arXiv:2504.16840.

Li, D., Quan, C., Song, Z., Li, X., Yu, G., Li, C. (2021). High-throughput plant phenotyping platform (HT3P) as a novel tool for estimating agronomic traits from the lab to the field. *Front. Bioeng. Biotechnol.*8.

Lozano-Claros, D., Meng, X., Custovic, E., Deng, G., Berkowitz, O., Whelan, J. (2020). Developmental normalization of phenomics data generated by high throughput plant phenotyping systems. *Plant Methods*16, 111.

Mahlein, A.K., Steiner, U., Hillnhütter, C., Dehne, H.W., Oerke,

ISSN (E): 2582 – 7022

E.C. (2012). Hyperspectral imaging for small-scale analysis of symptoms caused by different sugar beet diseases. *Plant Methods*8 (1), 1–13.

Roitsch, T., Cabrera-Bosquet, L., Fournier, A., Ghamkhar, K., Jimenez-Berni J.A., Pinto, F. et al. (2019). Review: New sensors and data-driven approaches—A path to next generation phenomics. *Plant Sci.*282, 2.

Stegemann, J., Groniger, F., Neutsch, K., Li, H.F., Metternich, J.T. (2024). Hyperspectral near infrared imaging using a tunable spectral phasor. *arXiv e-prints, arXiv-2407*.

Wu, C., Luo, J., Xiao, Y. (2024). Multi-omics assists genomic prediction of maize yield with machine learning approaches. *Mol. Breed.*44, 14.

Yang, W., Feng, H., Zhang, X., Zhang, J., Doonan, J.H., Batchelor, W.D. (2020). Crop phenomics and high-throughput phenotyping: past decades, current challenges, and future perspectives. *Mol. Plant*13, 187–214.