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Review Article

High-throughput Screening and Trait Dissection for Seed Quality Enhancement

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Abstract

High-throughput phenotyping (HTP) has transformed seed testing, quality evaluation, storage, and stress response assessment by enabling rapid, non-destructive, and high-resolution analysis of seed traits. Traditional seed evaluation methods are labour-intensive and time-consuming, whereas HTP employs advanced imaging, sensor technologies, and machine learning algorithms to assess seed morphology, physiological traits, and biochemical properties efficiently. In seed testing, HTP accelerates germination studies, vigour assessments, and stress tolerance evaluations, facilitating the identification of high-quality and resilient seed varieties. It also enhances seed storage practices by providing real-time monitoring of seed viability, detecting deterioration factors, and optimizing storage conditions. Furthermore, HTP significantly contributes to understanding seed responses to biotic and abiotic stresses. By characterizing genetic and physiological factors associated with disease resistance and environmental stress tolerance, HTP aids in breeding stress-resilient crops and optimizing seed treatments. The integration of HTP with artificial intelligence further refines predictive modelling and precision agriculture strategies, supporting climate-resilient farming and sustainable agricultural practices. This paper highlights the multifaceted role of HTP in advancing seed science, from quality assurance to stress management, underscoring its impact on agricultural productivity and genetic resource conservation.

Introduction

High-throughput phenotyping (HTP) represents a cutting-edge approach in plant science, revolutionizing the way researchers study and understand complex plant traits. This innovative method enables the rapid and non-destructive monitoring and measurement of multiple phenotypic traits related to growth, yield, and adaptation to various biotic or abiotic stresses [1]. At its core, it involves a systematic and comprehensive method for evaluating various characteristics of plants, spanning from their growth patterns to their physiological responses. High-throughput phenotyping provides a systematic approach to assessing diverse traits in plant populations, leveraging automated and scalable techniques. It aims to capture a broad spectrum of plant characteristics efficiently and accurately (Figure 1). These include high-resolution cameras and sensors that are employed to capture detailed images of plants from various angles and perspectives (Table 1) [2]. These images provide insights into morphological features such as leaf shape, size, and arrangement [3]. Various sensors are employed to measure critical parameters such as temperature, humidity, and nutrient levels in the plant's immediate environment. Additionally, specialized sensors can capture data related to plant physiological processes, such as photosynthesis and transpiration rates [4]. The collected

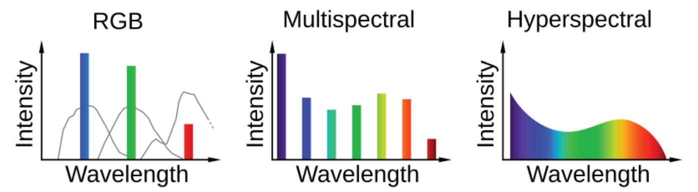

Figure 1: Different high-throughput sensors. https://commons.wikimedia.org/wiki/File:Spectral_sampling_RGB_multispectral_hyperspectral_imaging.svg [50].

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Table 1: Common imaging techniques used in HTP.

Imaging techniques	Details	Advantages	Reference
RGB	Collects electromagnetic radiation in the red, green and blue wavelengths, and captures snapshots at both nadir and off-nadir angles	RGB data can capture phenotypic details such as growth rate, plant height, canopy and vegetation cover models, disease detection, crop senescence, biomass and yield estimates	Das, et al. [19]
Multispectral	There is no set number of bands that distinguish a sensor as multispectral, but if a sensor has between 4 and 15 bands, it may be considered multispectral	Analysis of multispectral data from UAV systems has been shown to be successful in determining water content, disease detection, yield prediction, biomass, and nutrient uptake	Gano, et al. [20]
Hyperspectral	Captures hundreds of bands in a contiguous fashion from visible (VIS) to NIR to short-wave infrared (SWIR) ranges	Areas of hyperspectral spectroscopy success in plant phenotyping includes the extraction of both structural and physiological plant information, crop disease pathology, and plant stress and health	Sahoo, et al. [21]
Light Detection and Ranging (LiDAR)	Unlike the abovementioned passive sensors, LiDAR actively emits infrared laser pulses (primarily 800–1000 nm), measuring the return speed and intensity to determine target height and material properties	These data are analysed to assess crop growth and development phenotypes throughout a growing season, including height and above-ground biomass	Zhu, et al. [22]
Thermal	Between the spectral wavelengths of 3 and 14 μm lies the thermal imaging range of infrared radiation, with maximum atmospheric transmission occurring between 3-5 and 7-14 μm.	For plant phenotyping, thermal imaging or thermography is particularly useful for understanding leaf surface temperature, which relates to stomatal conductance and the rate of evaporation or transpiration	Moller, et al. [23]
Fluorescence	This sensor excels in detecting subtle changes in plants' structural and biochemical attributes at specific wavelengths (250 to 700 nm)	Differentiate between stressed and unstressed plants based on variations in their fluorescence emissions, which can be translated into photosynthetic responses.	Walsh, et al. [24]

data undergoes sophisticated analysis, often employing machine learning algorithms and statistical models. These analytical techniques help extract meaningful patterns and correlations from the vast amounts of data generated during the phenotyping process [5].

Automation plays a pivotal role in high-throughput phenotyping, facilitating the rapid and consistent assessment of numerous plants or plots. Automated systems can handle tasks like plant positioning, image capture, and data processing with minimal human intervention, significantly increasing throughput and reducing labour costs [6,7]. High-throughput phenotyping offers several advantages over traditional methods of trait assessment; by automating repetitive tasks and streamlining data collection and analysis, high-throughput phenotyping significantly reduces the time and effort required to characterize plant traits (Figure 2). This allows researchers to conduct large-scale studies more efficiently and explore a broader range of genetic or environmental factors influencing plant performance [7].

The use of advanced imaging and sensor technologies enhances the precision and reliability of trait measurements. This improved accuracy is particularly valuable in identifying subtle differences in plant responses to various treatments or conditions, aiding in the selection of superior crop varieties [8]. High-throughput phenotyping platforms can accommodate large numbers of plants or experimental plots, enabling researchers to generate extensive datasets with high spatial and temporal resolution. This scalability is essential for capturing the complexity of plant traits and understanding their interactions under diverse environmental conditions [9]. The wealth of data generated through high-throughput phenotyping provides valuable insights for crop improvement efforts. By identifying genetic variants or traits associated with desirable agronomic characteristics, researchers can accelerate the breeding process and develop crops better adapted to changing environmental conditions or emerging challenges,

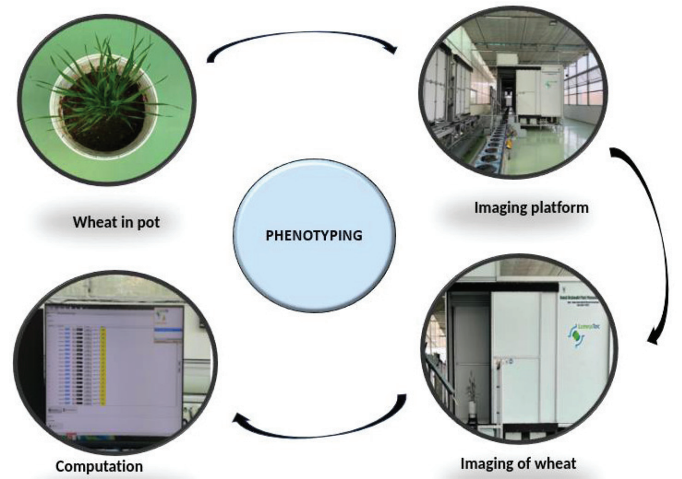

Figure 2: Plant phenotyping process.

such as pests and diseases [10]. Advanced algorithms and machine learning techniques are employed to process the vast amounts of data collected through imaging and sensor technologies. These analytical tools help extract meaningful phenotypic information from raw data, facilitating trait dissection and identification of correlations between genotype and phenotype [11]. Machine learning algorithms can recognize complex patterns and relationships within the data, allowing researchers to uncover hidden insights and predict plant responses to different environmental conditions or genetic variations [12].

Advancements in phenotyping

Tailored phenotyping approaches have been developed for different crops, such as wheat and maize, to identify traits related to climate resilience. These crop-specific phenotyping protocols take into account the unique characteristics and growth patterns of each crop, optimizing data collection and analysis strategies to maximize the detection of relevant traits.

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By focusing on traits associated with drought tolerance, heat tolerance, disease resistance, and other factors critical for climate resilience, crop-specific phenotyping contributes to the development of more resilient crop varieties [13]. High-throughput phenotyping is integrated with genetic analysis techniques, which include genome-wide association studies (GWAS) and genomic selection, to accelerate the identification of traits associated with climate resilience [14].

GWAS has become a powerful tool for dissecting the genetic architecture of complex traits in crops like maize. In maize, Genome-Wide Association Studies (GWAS) have significantly advanced the identification of genetic loci and candidate genes associated with complex traits, particularly those related to responses to abiotic and biotic stresses. These discoveries are paving the way for improved adaptability and yield through precision breeding strategies [15]. One of the key features of GWAS in maize is the rapid decay of Linkage Disequilibrium (LD), a result of the crop's rich genetic and phenotypic diversity. This low LD enhances the resolution of association mapping, making it easier to detect trait-linked loci with high precision [16]. GWAS has effectively identified quantitative trait loci (QTLs) associated with resistance to major diseases, including southern maize rust, leaf necrosis, Gibberella ear rot, Fusarium ear rot, and gray leaf spot. Additionally, it has pinpointed numerous genomic regions associated with abiotic stress tolerance, reflecting the underlying genetic diversity in traits like drought resistance, root structure, and plant architecture [17]. The method has become indispensable for exploring natural variation and dissecting quantitative traits, with the help of high-resolution genotyping platforms. This enables the discovery of novel alleles that can be harnessed to improve maize productivity and resilience under changing environmental conditions [15]. By combining phenotypic data with genomic information, researchers can pinpoint genetic markers linked to desirable traits, enabling more targeted breeding strategies. Integrating high-throughput phenotyping with genetic analysis also enhances the efficiency of trait selection and validation, leading to faster progress in crop improvement programs [18]. High-throughput phenotyping addresses bottlenecks in crop breeding by streamlining the process of trait evaluation and selection. By providing rapid and accurate phenotypic data, this approach accelerates the development of climate-resilient crop varieties, contributing to food security in the face of climate change. By enabling breeders to identify and prioritize traits associated with climate resilience more efficiently, high-throughput phenotyping enhances the overall effectiveness of crop breeding programs [9,12].

The classification and sorting of high-quality seeds are essential as they play a significant role in crop production. Traditional methods that rely on texture, shape, and colour are inefficient because they require repetitive work. Recently, deep learning has made significant advancements in image processing, with Deep Convolutional Neural Networks (DCNNs) commonly used for image classification tasks. In this study, another neural network called Vision Transformer (ViT) was explored. Originally applied in natural language processing, The Vision Transformer (ViT) architecture relies on self-attention mechanisms and omits convolutional structures. However, ViT struggles to train effectively on small and medium-sized datasets due to limitations in tokenization and local structure representation. To address these challenges, an improved ViT model named SeedViT was developed. SeedViT can train small and medium datasets to achieve state-of-the-art (SOTA) performance in vision classification with only 2,500 images. The feasibility of SeedViT for classifying maize seed quality was studied and compared with DCNNs and traditional machine learning algorithms. SeedViT demonstrated exceptional performance metrics with an accuracy of 97.6%, sensitivity of 94.1%, specificity of 98.9%, and precision of 97%. These results highlight its potential as a novel solution for efficient maize seed quality assessment [25]. To automate rice seed varietal identification, a vision transformer-based architecture called RiceSeedNet was developed by Rajalakshmi, et al. [7]. The proposed RiceSeedNet achieved an impressive accuracy of 97% in classifying 13 local varieties (Tamil Nadu, India) of rice seeds. Additionally, the model was also evaluated using a publicly available rice grain dataset to assess its performance across different rice grain varieties. In this cross-data validation, RiceSeedNet demonstrated exceptional results, achieving 99% accuracy in classifying 8 varieties of rice grains on the public dataset. The advancements in deep learning, particularly the application of Vision Transformers (ViTs), have revolutionized seed classification and quality assessment. Their high precision, sensitivity, and specificity highlight their reliability for practical deployment in agriculture.

Climate-resilient crops withstand multiple stress factors, including climate-driven, human-made, and biotic challenges. As extreme weather, water scarcity, and shifting pest patterns threaten agriculture, these crops ensure stable yields, food security, and economic stability. High-throughput phenotyping plays a crucial role in identifying and developing resilient crop varieties by analysing key traits. These crops reduce agricultural risks, require fewer inputs, and support environmental sustainability through resource-efficient practices and carbon sequestration [26]. Beyond farms, climate-resilient crops contribute to global climate change mitigation by reducing greenhouse gas emissions and promoting adaptation strategies [27]. Advancements in phenotyping accelerate breeding precision, unlocking genetic diversity for improved resilience. Collaborative efforts among scientists, policymakers, and farmers are essential for widespread adoption, ensuring long-term agricultural sustainability and global food security.

Managing and analysing large volumes of phenotypic data presents significant challenges, requiring robust data management and analysis frameworks. To overcome these challenges, researchers are developing scalable and interoperable data management systems capable of handling diverse data types and facilitating collaboration across research institutions and disciplines. The seamless integration of high-throughput phenotyping with breeding programs is crucial for translating phenotypic insights into practical applications. This requires close collaboration between phenotyping facilities,

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breeding organizations, and industry partners to ensure that phenotypic data are effectively utilized in breeding decisions and a variety of development processes [28]. High-throughput phenotyping holds immense potential to revolutionize crop breeding by enabling the rapid development of climate-resilient crop varieties [29]. By accelerating the identification and deployment of traits associated with climate resilience, high-throughput phenotyping can help mitigate the impact of climate change on agricultural productivity and ensure global food security. Continued advancements in imaging, sensor, and data analysis technologies will further enhance the capabilities of high-throughput phenotyping, paving the way for more efficient and sustainable crop improvement strategies [7].

High-throughput phenotyping and seeds

High-throughput phenotyping has revolutionized seed testing and quality evaluation processes, offering unparalleled efficiency, accuracy, and scalability. Traditionally, seed testing and quality evaluation relied on labour-intensive and time-consuming methods, limiting the speed and scope of analysis [30]. However, with high-throughput phenotyping techniques, researchers can rapidly assess numerous seed traits simultaneously, enabling comprehensive evaluations within a fraction of the time. One of the primary applications of high-throughput phenotyping in seed testing is the analysis of seed morphology and physical characteristics [31]. Automated imaging systems coupled with advanced algorithms can accurately measure seed size, shape, colour, and surface texture, providing valuable insights into seed quality and uniformity. By processing large volumes of seed samples quickly, high-throughput phenotyping facilitates the identification of outliers and abnormalities, ensuring only high-quality seeds are selected for further evaluation or commercial use. Moreover, high-throughput phenotyping enables the non-destructive assessment of seed physiological and biochemical traits, such as germination rate, Vigor, and seedling growth parameters [32]. Automated phenotyping platforms equipped with specialized sensors and imaging techniques can monitor seed germination dynamics in real-time, capturing subtle variations in seed performance under different environmental conditions. This real-time data acquisition allows researchers to identify superior genotypes with enhanced germination capacity and stress tolerance, facilitating the selection of resilient seed varieties for cultivation [33]. High-throughput phenotyping techniques have been instrumental in advancing seed health and disease resistance testing. High-resolution imaging combined with machine learning algorithms can detect pathogens, pests, and fungal infections at early stages of seed development, minimizing the risk of disease transmission and crop losses. Additionally, high-throughput phenotyping enables the screening of seed treatments and genetic modifications for their efficacy in enhancing disease resistance and promoting plant health, accelerating the development of resilient seed varieties tailored to specific agroecological conditions [34].

High-throughput phenotyping has revolutionized seed testing and quality evaluation processes, offering significant advantages over traditional methods. In seed testing, high-throughput phenotyping enables rapid and non-destructive assessment of multiple seed traits, including germination rate, seed Vigor, and stress tolerance. By employing automated imaging systems and advanced analytical techniques, high-throughput phenotyping allows for high-speed analysis of large seed populations, thereby increasing throughput and reducing testing time compared to manual methods [32]. High-throughput phenotyping facilitates the evaluation of seed quality across diverse environmental conditions, enabling breeders and seed producers to identify varieties with superior performance under specific stressors such as drought, salinity, or disease pressure [35]. This information is invaluable for selecting seeds with enhanced resilience to environmental challenges, ultimately contributing to more resilient and productive crop systems. HTP enables the assessment of seed traits at a finer resolution, providing insights into genetic variation and trait correlations that may not be apparent through traditional seed testing methods. This enhanced understanding of seed biology and physiology allows breeders to develop tailored breeding strategies aimed at improving seed quality and performance [36]. It plays a crucial role in seed certification and quality assurance programs by providing objective and reliable data on seed characteristics. By standardizing testing protocols and ensuring consistency in seed quality evaluation, HTP helps maintain the integrity of seed markets and enhances consumer confidence in seed products. The use of HTP in seed testing and quality evaluation has implications for the development of sustainable agriculture practices. By enabling the identification of seeds with improved stress tolerance and agronomic traits, HTP supports the development of crop varieties that require fewer inputs such as water, fertilizers, and pesticides, thereby promoting resource efficiency and reducing environmental impact [32,37].

Moreover, HTP contributes to the preservation and utilization of genetic diversity in seed banks and germplasm collections. By characterizing seed traits at scale, HTP enables the comprehensive assessment of genetic resources for traits of interest, facilitating the identification of valuable genetic materials for breeding programs and conservation efforts. This enhanced understanding of genetic diversity supports efforts to develop resilient crop varieties adapted to changing environmental conditions and emerging challenges. Additionally, HTP has applications in seed treatment and processing, enabling the rapid assessment of seed viability, uniformity, and quality following treatments such as priming, coating, or inoculation. By providing real-time feedback on seed quality parameters, HTP ensures the efficacy and consistency of seed treatments, thereby enhancing crop establishment and performance in the field [38]. Furthermore, the integration of HTP with emerging technologies such as artificial intelligence and machine learning holds promise for further advancing seed breeding and quality evaluation processes. By leveraging data analytics and predictive modelling, HTP can identify complex trait interactions and optimize breeding strategies for maximum genetic gain and trait expression [12].

High-throughput phenotyping and seed storage

High-throughput phenotyping has significant implications

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for seed storage practices, particularly in terms of quality assessment, management, and preservation. One of the primary effects of HTP on seed storage is its ability to provide rapid and non-destructive evaluation of seed quality before storage [39]. By employing advanced imaging techniques and automated analysis, HTP enables seed producers and seed banks to assess key quality parameters such as viability, germination rate, and Vigor quickly and accurately. This pre-storage assessment helps identify seeds with optimal characteristics for long-term storage, ensuring that only high-quality seeds are preserved, thus minimizing storage losses and maximizing seed viability over time [40]. Moreover, HTP facilitates the monitoring of seed storage conditions and detection of potential deterioration factors as depicted in Figure 3. By analysing changes in seed traits and physiological responses over time, HTP can provide insights into the effectiveness of storage conditions such as temperature, humidity, and oxygen levels. This real-time monitoring allows seed managers to adjust storage conditions accordingly to maintain seed quality and prolong storage longevity [32]. Additionally, HTP enables the early detection of storage-related issues such as seed deterioration, insect infestation, or fungal contamination, allowing for timely interventions to prevent further damage and preserve seed integrity. HTP contributes to the development of improved seed storage protocols and technologies aimed at enhancing seed longevity and quality. By identifying genetic and physiological factors influencing seed storability, HTP informs the design of storage facilities, packaging materials, and seed treatment methods optimized for preserving seed viability and Vigor over extended periods. Additionally, HTP facilitates research into novel seed storage techniques such as cryopreservation, desiccation, or controlled atmosphere storage, which offer alternative approaches for maintaining seed quality under challenging environmental conditions or for long-term conservation purposes [39].

High-throughput phenotyping enhances the efficiency and effectiveness of seed storage management through its ability to analyse seed traits associated with storage longevity and stress tolerance. By characterizing genetic and physiological factors related to seed storability, such as seed coat permeability, lipid composition, and antioxidant capacity, HTP enables the selection and preservation of seeds with enhanced resilience to storage-related stresses. This targeted approach to seed selection ensures the retention of high-quality germplasm in seed banks and conservation repositories, ultimately safeguarding genetic diversity and agricultural resilience. HTP facilitates the identification of molecular markers and genetic pathways associated with seed longevity and storage-related traits. By integrating genomic data with phenotypic information, HTP enables researchers to unravel the genetic basis of seed storage traits, facilitating marker-assisted breeding and genetic engineering approaches aimed at improving seed storability and shelf life. This molecular understanding of seed storage mechanisms offers opportunities for the development of tailored interventions to enhance seed quality and longevity, thereby reducing losses during storage and ensuring the availability of viable seeds for future generations [32]. It supports the optimization of seed drying and conditioning processes essential for long-term storage. By assessing seed moisture content, dormancy status, and physiological maturity, HTP helps determine optimal drying protocols tailored to specific seed species and storage requirements. This precision drying approach minimizes the risk of seed damage or deterioration during storage and ensures the preservation of seed viability and vigour over time. The application of HTP in seed storage extends beyond traditional agricultural crops to encompass a wide range of plant species, including wild relatives, rare and endangered species, and non-traditional crops with ecological or economic importance. By enabling the systematic characterization and conservation of diverse seed resources, HTP contributes to biodiversity conservation efforts, restoration initiatives, and ecosystem resilience in the face of environmental change and habitat loss. In addition to its direct impact on seed quality assessment and storage monitoring, high-throughput phenotyping also plays a crucial role in seed bank management and seed conservation efforts. Seed banks serve as repositories of genetic diversity, preserving a wide range of crop varieties and wild plant species for future use in breeding, research, and conservation. HTP technologies offer several advantages in this context, including the rapid characterization of seed traits, the identification of valuable genetic resources, and the optimization of seed bank operations [41].

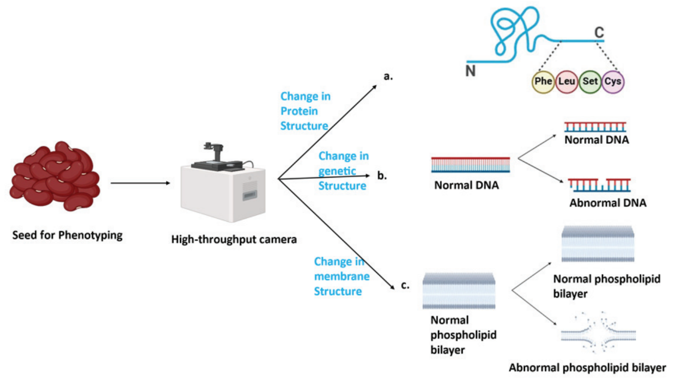

Figure 3: Schematic representation of physiological and structural changes in seeds during storage. a. Depicts alterations in protein conformation and denaturation over time, which may affect enzyme activity and metabolic stability. b. Illustrates modifications in chromatin structure, including changes in both structural and storage-associated chromosomes, potentially impacting gene expression and seed viability. c. Shows disruption in the phospholipid bilayer of cellular membranes, leading to loss of membrane integrity and reduced cellular function during prolonged storage

HTP enables seed banks to efficiently evaluate large seed collections for traits of interest, such as stress tolerance, disease resistance, or nutritional content. By automating the process of seed trait analysis, HTP significantly reduces the time and labour required for seed characterization, allowing seed banks to handle larger seed collections and prioritize resources more effectively. This increased efficiency is particularly beneficial for seed banks managing diverse collections of crop landraces, wild relatives, and endangered species, where comprehensive trait evaluation is essential for prioritizing conservation efforts and facilitating utilization in breeding programs. It facilitates

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the identification of valuable genetic resources within seed bank collections, aiding in the selection of accessions with unique or rare traits for conservation and utilization purposes. By systematically screening seeds for desirable characteristics, such as drought tolerance or resistance to pests and diseases, HTP helps seed banks identify potential candidates for breeding programs aimed at developing climate-resilient crop varieties or restoring endangered plant populations [27]. Additionally, HTP enables seed banks to track changes in seed traits over time, providing valuable insights into seed conservation dynamics and informing strategies for genetic resource management and utilization. Furthermore, HTP supports efforts to improve seed bank infrastructure and seed conservation techniques through data-driven research and innovation. By analysing the impact of storage conditions, seed handling procedures, and conservation strategies on seed viability and longevity, HTP helps optimize seed bank protocols to enhance seed preservation and minimize genetic erosion. Additionally, HTP facilitates research into novel seed conservation techniques, such as cryopreservation, tissue culture, or in vitro storage, which offer alternative approaches for preserving seeds with limited longevity or viability under traditional storage conditions [34].

High-throughput phenotyping and its impact on seeds during biotic stress

High-throughput phenotyping (HTP) has a profound effect on seeds during biotic stress, offering valuable insights into seed responses to pathogen and pest pressure. By employing automated imaging systems and advanced analytical techniques, HTP enables the rapid and non-destructive assessment of seed traits related to biotic stress resistance, including seedling Vigor, disease susceptibility, and pest damage. This real-time monitoring and characterization of seed responses to biotic stressors provide critical information for breeders, researchers, and farmers aiming to develop resilient crop varieties and implement effective pest and disease management strategies. One significant effect of HTP on seeds during biotic stress is the early detection and characterization of resistance mechanisms [42]. HTP allows for the precise quantification of seed traits associated with resistance, such as lesion size, pathogen growth inhibition, or pest-feeding behaviour, enabling researchers to identify genetic factors underlying resistance and breed for improved resistance in future generations. Additionally, HTP facilitates the screening of large seed populations for natural variation in resistance traits, aiding in the selection of resistant germplasm for breeding programs aimed at developing cultivars with enhanced biotic stress tolerance. It enables the rapid evaluation of seed treatment methods and crop protection products for their efficacy against biotic stressors. By monitoring changes in seed traits following treatment with fungicides, insecticides, or biological control agents, HTP helps assess the effectiveness of different management strategies in controlling pathogens and pests at the seedling stage. This information guides farmers and agronomists in selecting appropriate seed treatments and integrated pest management practices to minimize seed damage and maximize crop yield potential. HTP contributes to the development of predictive models and decision support tools for biotic stress management in seed production and crop cultivation. By integrating phenotypic data with environmental factors and disease or pest incidence records, HTP enables the development of models that predict seed susceptibility to biotic stress under varying conditions. These predictive models empower farmers to make informed decisions regarding seed selection, planting timing, and crop rotation strategies, thereby reducing the risk of biotic stress outbreaks and optimizing yield outcomes [9,43]. Convolutional neural network (CNN) fashions skilled in large datasets of plant snapshots can correctly discover and classify numerous illnesses and stress signs, frequently outperforming human professionals in phrases of velocity and accuracy. "Plant Village", a publicly available dataset of plant disorder photos, has been used to train deep learning models capable of identifying diseases in diverse crop species. These fashions can distinguish among one-of-a-kind types of foliar sicknesses based totally on a leaf, supplying a valuable device for early ailment detection and management in agricultural settings [44]. Another promising technique is the use of graph neural networks (GNNs) to version the complex interactions among unique organic entities. The GNN version represents genes, metabolites, and other biological entities as nodes in a graph, with edges representing recognized or anticipated interactions. By propagating statistics via this graph shape, the model can capture complicated relationships that may not be apparent while reading each fact type in isolation. For example, the Arabidopsis identified several metabolic genes that play key roles in coordinating responses to environmental pressure, bridging primary and secondary metabolism. These findings offer new targets for metabolic engineering efforts geared toward enhancing plant pressure tolerance and productivity. Thus, high-throughput phenotyping has transformative effects on seeds during biotic stress, enabling early detection of resistance mechanisms, evaluation of treatment efficacy, and development of predictive models for effective stress management. By providing valuable insights into seed responses to pathogens and pests, HTP supports the development of resilient crop varieties and sustainable pest and disease management practices, ultimately enhancing agricultural productivity and food security [29]. Continued investment in HTP research and technology transfer efforts is essential to further unlock its potential in addressing biotic stress challenges and advancing crop protection strategies in a changing climate and global context.

High-throughput phenotyping and its impact on seeds during abiotic stress

High-throughput phenotyping significantly impacts seeds during abiotic stress events, including drought, heat, cold, salinity, and nutrient deficiency. These stressors can significantly impact seed quality, viability, and germination, leading to reduced crop yields and agricultural productivity. However, HTP offers valuable tools and insights to mitigate the adverse effects of abiotic stress on seeds and enhance their resilience to environmental challenges. One of the primary effects of HTP on seeds during abiotic stress is the rapid and comprehensive assessment of stress-induced changes in

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seed traits [45]. By employing automated imaging systems, sensor technologies, and data analytics, HTP enables the real-time monitoring and quantification of physiological and biochemical responses in seeds exposed to abiotic stressors. This allows researchers and breeders to identify stress-related traits, such as osmotic adjustment, antioxidant capacity, or membrane stability, and assess their impact on seed quality and performance [46]. Moreover, HTP facilitates the screening of large seed populations for stress tolerance and resilience traits, enabling breeders to identify promising germplasm or genetic resources with enhanced adaptability to specific abiotic stress conditions. By systematically evaluating seed responses to stress under controlled laboratory or field conditions, HTP accelerates the selection of resilient varieties and the development of crop cultivars with improved stress tolerance. This proactive approach to breeding helps mitigate the impact of abiotic stress on seed quality and yield stability, contributing to agricultural sustainability and food security. HTP supports the development of precision agriculture strategies aimed at optimizing seed management practices in response to abiotic stress conditions. By integrating phenotypic data with environmental sensors, weather forecasts, and crop modelling tools, HTP enables farmers to make informed decisions regarding seed selection, planting schedules, irrigation management, and nutrient application. This data-driven approach enhances resource efficiency, reduces input costs, and minimizes yield losses associated with abiotic stress events, ultimately improving the resilience and profitability of agricultural systems [37].

Additionally, HTP facilitates research into novel seed treatments and technologies for enhancing seed resilience to abiotic stress. By screening seed treatments, priming techniques, or seed coating formulations, HTP helps identify strategies for improving seed germination, establishment, and early growth under stressful environmental conditions. This research contributes to the development of innovative solutions for mitigating the effects of abiotic stress on seed quality and crop performance, thereby supporting sustainable agriculture practices and climate change adaptation efforts. In addition to its direct impacts on seed quality assessment and breeding efforts, high-throughput phenotyping plays a critical role in elucidating the underlying physiological and molecular mechanisms governing seed responses to abiotic stress [47]. Through the analysis of large-scale phenotypic data, HTP allows researchers to identify key genes, pathways, and regulatory networks involved in stress tolerance and adaptation in seeds. This molecular-level understanding provides valuable insights into the genetic basis of stress resilience, facilitating the development of targeted breeding strategies and genetic engineering approaches to enhance seed performance under adverse environmental conditions [48]. HTP enables the evaluation of seed responses to multiple stress factors simultaneously, mimicking the complex and dynamic nature of real-world growing conditions. By subjecting seeds to controlled stress treatments in high-throughput screening platforms, researchers can assess the interactive effects of different stressors and identify genotype-by-environment interactions that influence seed resilience. This integrated approach enhances our understanding of the complex interactions between genetic and environmental factors shaping seed responses to abiotic stress, enabling more effective breeding and management practices tailored to specific agroecological contexts [49]. Moreover, HTP supports efforts to develop predictive models and decision-support tools for optimizing seed selection and management strategies in response to abiotic stress conditions. By integrating phenotypic data with environmental and agronomic variables, such as soil moisture, temperature, and precipitation, HTP enables the development of machine learning algorithms and predictive models to forecast seed performance and yield outcomes under different stress scenarios. These tools empower farmers and seed producers to make informed decisions regarding seed selection, planting schedules, and agronomic practices, enhancing resilience and productivity in the face of unpredictable environmental variability [41].

Conclusion

High-throughput phenotyping (HTP) is transforming seed science with rapid, non-destructive assessments of seed quality, resilience, and performance. By integrating advanced imaging, automation, and AI-driven analytics, HTP enhances seed testing, breeding, and stress tolerance screening, supporting sustainable agriculture. Future advancements—such as multi-omics approaches, portable phenotyping tools, and blockchain-based quality assurance—will further optimize seed selection, traceability, and market transparency, thereby shaping the future of global food systems.

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