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Digital Tools and Data Science in Plant Breeding

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INTRODUCTION

Crop yields, quality, nutrition, and stress tolerance have all been improved by plant breeding. But an expanding population, changing climate and finite natural resources mean that breeding methods must evolve to be faster and more accurate. The convergence of digital and computational technologies has revolutionized traditional breeding into a data centric discipline by allowing the collection, analysis and interpretation of genetic, phenotypic, and environmental information in an effective manner. Cutting-edge technologies such as artificial intelligence, machine learning, genomics, remote sensing and big data analysis are facilitating the breeding of better crops, heralding a new era of accuracy and creativity in plant breeding.

What are Digital Tools in Plant Breeding

Digital tools are system based on digital technology that is applied to the processes of capturing, managing, analyzing, and visualizing breeding data. The tools allow breeders to make informed decisions at all stages of the breeding process, including the evaluation of germplasm through to variety release.

Major Digital Tools Used in Plant Breeding

Current plant breeding consumes data from multiple sources and utilizes many a digital tool and technique, such as mobile field data collection applications, Geographic Information Systems (GIS), Global Positioning Systems (GPS), remote sensors, Unmanned Aerial Vehicles (UAV) or drones, genotyping platforms, and high-throughput phenotyping systems. Furthermore, computational advanced tools, such as Artificial Intelligence (AI), Machine Learning (ML), Decision Support Systems (DSS), cloud-based databases, and bioinformatics

software are fundamental for breeding data management and analysis. These technologies, when combined, allow plant breeders to capture, store, analyze and make decisions from large, complex data sets more effectively and efficiently to increase selection accuracy, speed breeding decisions, and the overall efficiency of the crop improvement program.



Understanding Data Science in Plant Breeding

Data science is the process of gathering, processing, and analyzing massive volumes of data via statistical methods, computational tools, machine learning, and predictive analytics. In plant breeding, it integrates genotypic (DNA markers, SNPs, and genome sequences), phenotypic (yield, quality, disease resistance, and stress tolerance traits) and environmental (temperature, rainfall, soil properties and other climatic factors) data. The combination of these datasets allows breeders to explore genotype $\times$ environment interactions, to increase selection accuracy, and to more rapidly identify superior

breeding lines in the development of high-performing crop varieties.

Role of Digital Tools in Modern Plant Breeding

1. Germplasm Characterization

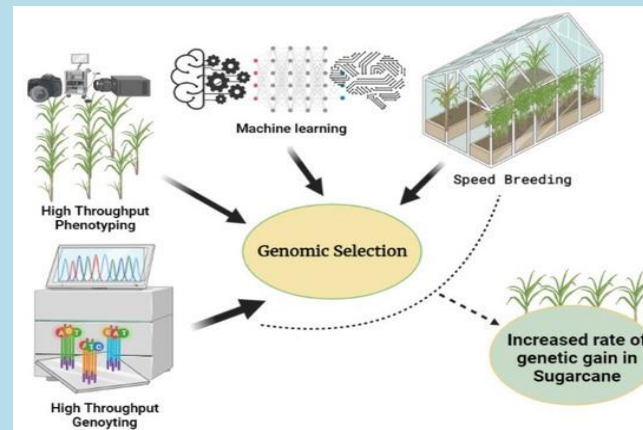
Characterization of germplasm allows for the detection of useful genetic resources for crop improvement. With the help of digital databases, molecular markers and genomic tools, such vast germplasm can be assessed and documented effectively. These technologies allow breeders to evaluate genetic diversity and focus that diversity on genes that are breeding targets to develop enhanced crop varieties.

2. High-Throughput Phenotyping

High Throughput Phenotyping is the use of advanced phenotyping tools such as Unmanned Aerial Vehicles (UAVs), proximal sensors, imaging systems and automated platforms to quickly capture plant traits. It enables accurate measurement of traits such as plant height, biomass, leaf area, and disease symptoms. This method dramatically enhances the efficiency of breeding.

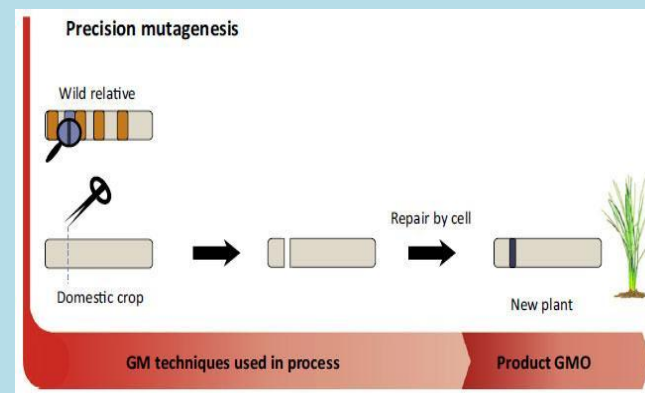
3. Genomic Selection

Genomic prediction is a form of marker-assisted selection where genome-wide marker information is used to predict the breeding value of plants prior to field evaluation. It allows increasing the rate of selection, the accuracy of the prediction and the genetic gain. This technology makes it possible for breeders to create enhanced varieties faster and more economically.



4. Precision Breeding

Precision breeding uses molecular and digital tools to pinpoint genes linked to desirable traits. Methods like marker-assisted selection, and genomic assisted breeding, facilitate focused and precise selection. This method increases breeding efficiency and accelerates line development of better crop varieties.



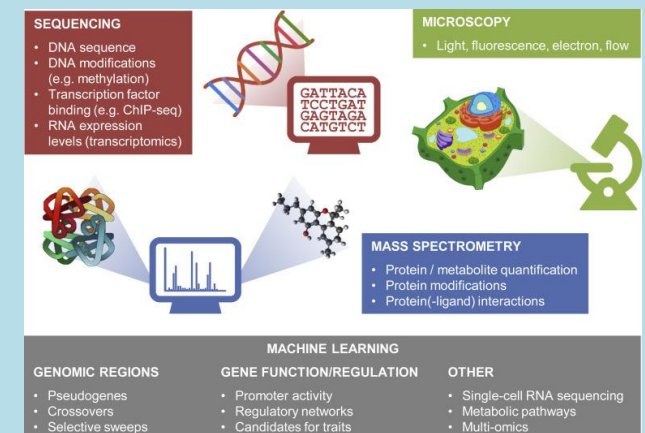
5. Data Management and Analysis

Contemporary breeding schemes produce vast amounts of genetic, phenotypic, and environmental data. Digital databases and cloud computing platforms

enable storing, managing, analyzing and sharing the information in a more efficient way. These tools allow better informed decisions, efficient workflow management, and facilitate collaboration among scientists.

Artificial Intelligence and Machine Learning in Plant Breeding

New technologies such as Artificial Intelligence (AI), drones, remote sensing and big data analysis are revolutionizing today's plant breeding. AI can be used to accurately predict complex traits, detect diseases, select superior genotypes, and optimize breeding strategies.



Drones with advanced sensing and imaging technologies can efficiently conduct dynamic, low-cost, real-time field surveillance; meanwhile, remote sensing has the potential to nondestructively evaluate crop traits such as biomass, water stress, nutrient status, disease exposure, and yield potential. Moreover, big data analytics combines data from genomics, phenomics, environmental monitoring and field trials to discover important patterns and enhance decision-making.

Benefits of Digital Tools and Data Science in Plant Breeding

The use of digital technologies and data science in plant breeding helps to realise potential economic, scientific, environmental, and social benefits. From an economic perspective, these technologies decrease the cost of breeding, increase the speed of variety development, increase efficiency in resource use, and enable higher returns on investment. Scientifically, they increase the accuracy of selection, lead to a better understanding of genetic architecture, increase genetic gain, and allow more accurate prediction of the results of breeding. Environmentally, they enable the creation of climate-adapted crop solutions, minimize resource wastage, and facilitate sustainable agriculture production. In the social domain, they help to enhance food and nutrition security, bolster farmer livelihoods, and catalyze the evolution of sustainable agriculture.

Challenges in Digital Plant Breeding

The barriers to widespread use of digital breeding technology remain high despite the progress that has already been made. There are other issues, including limited access to the technology in developing countries, as well as concerns over data privacy and security. These limitations must be overcome to fully exploit the digital and data science tools in contemporary plant breeding.

Future Perspectives

The future of plant breeding will be shaped by combining genomics, phenomics, artificial intelligence, robotics, and big data analytics. The smart breeding platforms, digital twins, AI-assisted breeding and autonomous field phenotyping systems are some of the emerging technologies that will allow

for more precise prediction, selection, and assessment of crop traits. These innovative tools, together with climate-smart breeding strategies, will accelerate the development of resilient, high-yielding crop varieties, increase genetic gains, and support sustainable agricultural production in the face of environmental change.

CONCLUSION

Digital technology and data science are revolutionizing plant breeding, allowing development of crops that are better adapted to the environment at a faster pace with more precision and based on data. Advances in genomics, high-throughput phenotyping, artificial intelligence, remote sensing, and big data analytics are enabling breeders to challenge tradition and expedite the creation of high-yielding, climate-resilient, and nutritious crops. With the pressures of feeding a growing population and adapting to climate change ever-increasing on global agriculture, digital breeding techniques are expected to be critical in delivering food security, sustainability, and agricultural innovation in the twenty-first century.