iJRASET
International Journal For Research in
Applied Science and Engineering Technology

INTERNATIONAL JOURNAL FOR RESEARCH

IN APPLIED SCIENCE & ENGINEERING TECHNOLOGY

Volume: 14 Issue: III Month of publication: March 2026

DOI: https://doi.org/10.22214/ijraset.2026.78089

AI-Driven Innovations in Plant Biotechnology for Sustainable Agriculture

Dr. Neeraj K. Charmkar[1]
[1]Assistant Professor of Botany, PMCOE, Govt. Model Science College Rewa (M.P)

Abstract: ***Plant biotechnology is evolving through Artificial Intelligence (AI) to combine computational intelligence and genomic science to enhance growth in crops and sustainable agricultural systems. This paper trying to reveal the genomic innovation driven by AI will be deeply analyzed with focus on the machine learning-assisted genome sequencing, optimization in gene editing, and prediction in traits.***

Complex algorithms help to locate the quantitative trait loci, resistant genes to stress and metabolic pathways, thus resulting in more accurate breeding and CRISPR-mediated treatments. The digital twins, or virtual models of crops or plants, come up as a disruptive technology, allowing to simulate the growth process and its interaction with the environment and predict yields in real time, in a variety of climatic conditions.

AI increases crop management and resource allocation decision-making through the combination of high-throughput phenotyping, remote sensing, and big data analytics.

Moreover, AI-enabled combination of omics (genomics, transcriptomics, proteomics and metabolomics) enhances systems biology strategies of climate-resilient and nutrient-efficient crops. Another issue discussed in the study is the ethical concerns, data management, and the digital divide among smallholder farmers. Conclusively, plant biotechnology based on AI is a groundbreaking direction to food security, less carbon impact and sustainable intensification of agriculture in the age of climate change and population explosion.

Keywords: ***Artificial Intelligence, Plant Biotechnology, Genomic Innovation, Digital Twins, Sustainable Agriculture etc.***

I. INTRODUCTION

Modern agricultural science is facing a nexus of new threats that threatens the stability of the world food system. As the human population is expected to hit ten billion by 2050, the demand of food, feed and fiber is set to increase significantly as well 【1】. Simultaneously, the mounting consequences of the climate change undermine the access to the arable land with frequent extreme weather conditions, salinization of the soils, and changing pests pressures [1].

Despite the historic and material gains associated with conventional breeding of plants alongside biotechnological interventions, they are being seen as somehow too slow and inaccurate to meet these surging demands in the necessary timelines[1] . As a result, the industry has begun a new era of intelligent design, characterized by the extreme-level adoption of artificial intelligence (AI), big-data analytics and advanced molecular biology[4].

Historically, plant breeding has taken place through a series of technological periods with the initial conscious selection of beneficial characteristics that took place during domestication approximately a decade ago[5].

The twentieth century has witnessed the introduction of hybrid breeding and the Green Revolution followed by the age of molecular breeding where marker-assisted selection and new genetic engineering were used to provide characteristics including herbicide resistance[1].

The current shift to a data-centric model represents a paradigmatic change in the nature of inquiry between observation-based science and a predictive science driven by engineered design[1]. Artificial intelligence, in particular deep-learning technologies and generative models, are being used to solve the complex genomic code of plants, mining the multi-omics data to identify so-called elite alleles and predict protein-structure using tools like AlphaFold[1].

International Journal for Research in Applied Science & Engineering Technology (IJRASET)
ISSN: 2321-9653; IC Value: 45.98; SJ Impact Factor: 7.538
Volume 14 Issue III Mar 2026- Available at www.ijraset.com

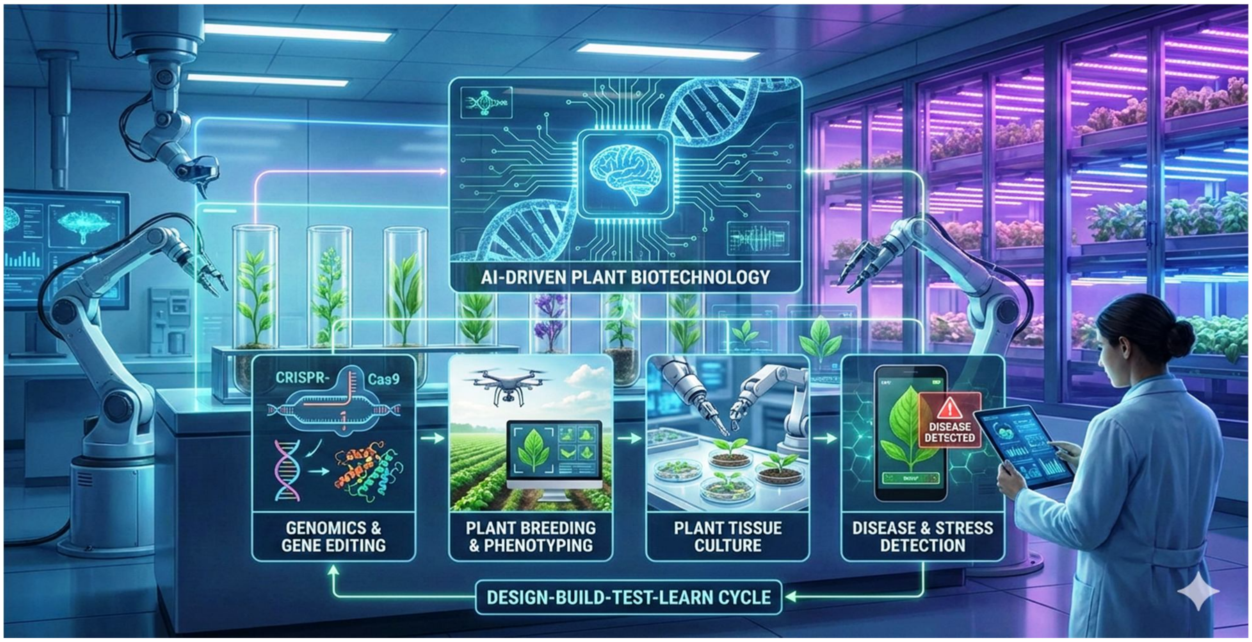

Diagram 1 - Various Approaches of AI in Plant Biotechnology.

This report examines the specific applications of AI across this spectrum, ranging from genome editing and tissue culture to the emergence of digital twins and the socio-economic implications for global bioeconomies, with a particular focus on the burgeoning ecosystem in India.[7]

Diagram 2 – Potentials of AI in Plant Biotechnology.

II. METHODS

Artificial intelligence introduction into plant biotechnology requires an entire methodological framework that incorporates hardware and software computing, and biological functionality. The core of this paradigm is that high-dimensional data will be acquired and processed in several strata of biological and environmental environment.

The plan to acquire data merges the area of genomics, the study of phenomena, and the monitoring of the environment. The building of vast genomic databases of staple crops (rice, corn, and wheat) by high-throughput sequencing and microarray technologies facilitates the input of machine-learning (ML) and deep-learning (DL) models that locate functionally relevant genes and regulatory loci.[4] In the phenomics field, data sets are gathered using unmanned aerial vehicles (UAVs), ground-based robotic platforms, and stationary sensor arrays that have multispectral, hyperspectral and thermal imaging capabilities.[4] In the phenomics field, data are measured on ground.

A range of AI architecture is used in data processing. The often utilised models of supervised learning, such as support vector machines (SVMs), random forests (RF), and k -nearest neighbors (kNN) are frequently used in classification and regression tasks in disease detection and yield forecasting.[13] Deep-learning architecture, especially convolutional neural networks (CNNs) and transformer models are preferred in image-based trait extraction and identifying sophisticated pattern in protein structures.[2] Finally, explainable AI (XAI) methods enable the multilayer analysis of such multilayered datasets and aim to demystify the black box of deep learning and provide researchers with the ability to see the exact mechanisms behind the response of the plant in a manner comprehensible to humans.[20]

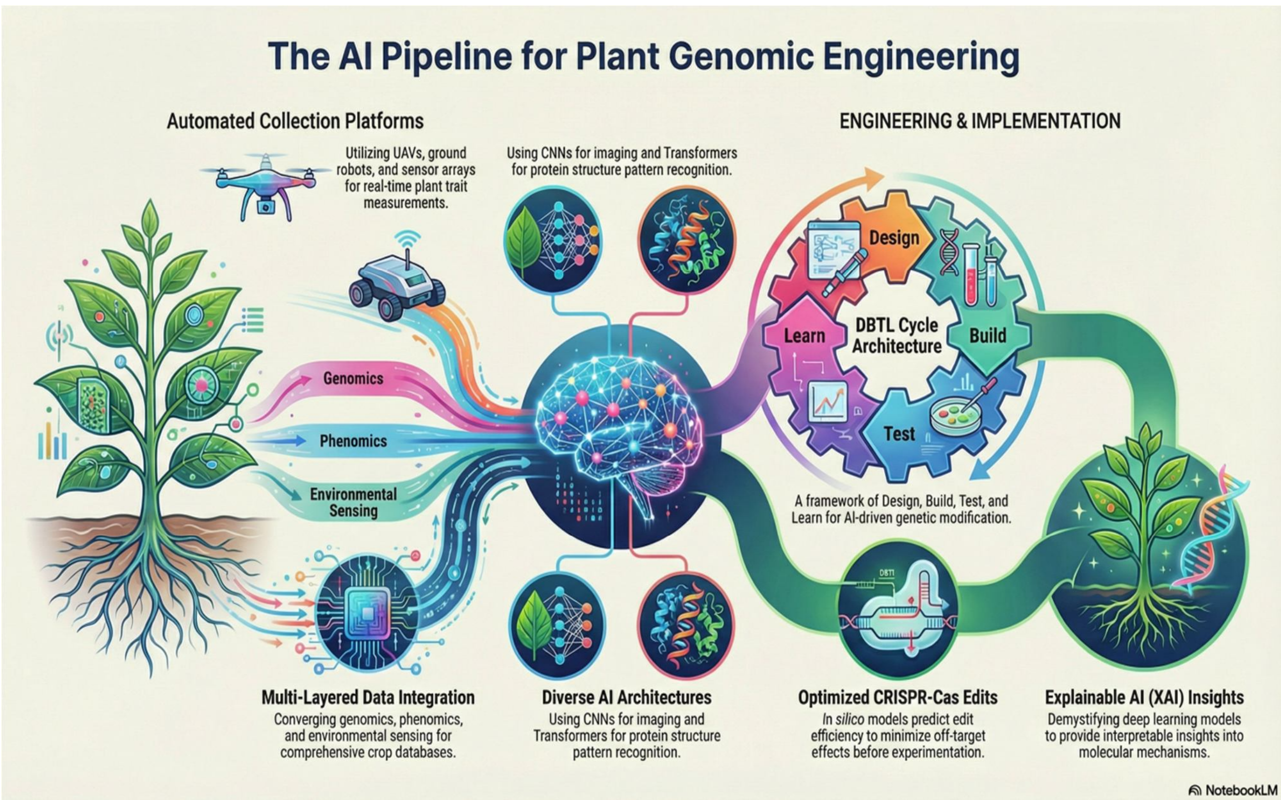

Diagram 3 – Integration of AI in Genetic Engineering & Plant Biotechnology.

III. RESULTS

A. AI-Enhanced Genome Editing and Precision Mutagenesis

The addition of artificial intelligence to the process of genome editing has made the CRISPR -Cas9 system not only a potentially helpful instrument but also an extremely specific one. Despite the fact that CRISPRRNA allows targeted DNA binding, challenges, which include off-target effects (OFTE) and locus-dependent activities, have remained significant impediments.10 AI-based models have repeatedly shown high to predict these parameters, and thus allowed the generation of single-guide RNAs (sgRNAs) with an improved specificity and activity.[18]

Deep learning algorithms are superior to more traditional machine-learning frameworks in that they are intrinsically able to detect non-linear relationships between large genomic sets, and achieve high accuracy and area under the curve (AUC) metrics of deterministic prediction of CRISPR-Cas9 cleavage positions in plant genomes: in one study, Random Forest models estimate accuracy at securing scores of 96.27 per cent and area under the curve (AUC) of 99.21 over, respectively.[13] A breakthrough in this area is the Plant-optimized AI-designed (PAiD) platform which uses AI-designed nucleases like OpenCRISPR-1.[24] which are designed to provide high knockouts, base editing, and prime editing in plant cells with equivalent efficiencies to those of traditional SpCas9.[24] AI-based methodologies are also being utilized to predict protein-nucleic acid interactions, simplifying the generation of gene-editing tools with enhanced stability and specificity.[17]

Model Category	Specific Algorithm/Platform	Primary Application	Key Metric/Outcome
Traditional ML	Random Forest (RF)	Cleavage site prediction	96.27% accuracy [13]
Deep Learning	CNN (Deep-CRISPR)	sgRNA activity/off-target	Automated feature extraction [10]
Generative AI	OpenCRISPR-1 / PAiD	De novo nuclease design	Robust prime/base editing [24]
Ensemble	XG-Boost / RF	Yield and trait prediction	High predictive accuracy [4]
Language Models	Protein LM	Protein-DNA interactions	Enhanced enzyme stability [17]

Table 1. – AI enhanced Platforms and applications.

B. *Optimization of Plant Tissue Culture and Micropropagation*

Plant tissue culture (PTC) is critical to the fast cultivation of elite cultivars and the manufacture of gene-edited cells.26 However, optimization of PTC protocols is still complex due to the complex interactions among the constituents of the media, hormone concentrations, and environmental factors.[28] A genetic algorithm was used to optimize the concentrations of four major hormones that induce the callus in Petunia and achieve a 95.83% success rate, a result that would have otherwise required extensive manual work.[28] It has become key to the high-speed propagation of elite cultivars and the regeneration of genetically edited cells.[26] that said, the optimization of PTC protocols has continued to be difficult due to the complexity of interplay between culture components, the levels of cultivation-relevant hormones, and the condition of the environment.[26] Precise and accurate robotic manipulators are also further facilitated through artificial intelligence enhanced vision systems to carry out delicate tasks, such as explant transfer and subculture with associated precision, and hence significantly reduce the chance of microbial contamination.

C. *AI in High-Throughput Phenotyping and Genomic Selection*

The integration of AI with high-throughput phenotyping (HTP) and genomic selection (GS) is accelerating the development of resilient crop varieties.[2] HTP platforms generate massive datasets that capture the dynamic physiological responses of plants to their environment.[1] AI algorithms process this data to provide a comprehensive view of crop health, often detecting subtle phenotypic changes before they are visible to the human eye.[31] AI models, particularly those based on deep learning, are increasingly used in GS because of their ability to model the complex, non-linear relationships between genotypes and phenotypes.[2] In a recent case study, the AutoGP breeding platform integrated multi-omics data from maize to guide the selection of superior hybrids, significantly enhancing breeding efficiency.[2]

D. *Plant Digital Twins and Prescriptive Agriculture*

A burgeoning trend in plant biotechnology is the creation of digital twins-virtual replicas of physical plants or farming systems that are continuously updated with real-time data.[33] These digital twins enable the simulation of agricultural processes, allowing researchers to predict how a specific genotype will respond to various environmental stressors or management practices before any physical intervention occurs.[34] Using technologies like Neural Radiance Fields (NeRF), researchers can convert 2D video footage of plants into high-fidelity 3D digital models, capturing millions of data points regarding color, shape, and structure.[38]

International Journal for Research in Applied Science & Engineering Technology (IJRASET)
ISSN: 2321-9653; IC Value: 45.98; SJ Impact Factor: 7.538
Volume 14 Issue III Mar 2026- Available at www.ijraset.com

Application Area	Digital Twin Capability	Technological Driver	Potential Benefit
Irrigation	Dynamic scheduling	IoT / Soil sensors	25% water savings [36]
Yield Forecasting	Predictive modeling	Satellite / UAV data	Early financial planning [33]
Trial Management	Virtual scenario testing	AI / Big data	Reduced cost/time [34]
Plant Growth	3D structure analysis	NeRF / Point clouds	Precise phenotyping [38]
Greenhouse	Autonomous control	AI / LUNA platform	Resource optimization [41]

Table 2. – Applications of AI in various areas.

E. *Disease and Pest Detection via Deep Learning*

Deep learning has revolutionized the identification of biotic stressors in agriculture. Traditional disease detection often relies on manual scouting, which is labor-intensive and prone to error.[31] AI-powered computer vision models have achieved state-of-the-art accuracies in identifying pests and pathogens from digital images.[16] Classification models using CNNs have consistently exceeded 95% accuracy in identifying plant diseases, while detection and segmentation networks have demonstrated precision rates above 90%.[16] For example, the DGVGNet model was developed to detect leaf diseases under challenging conditions such as shadows and occlusions, achieving a classification accuracy of 99.19%.[45] Lightweight models like MobileNet have also been optimized for edge computing, allowing for real-time diagnostics on mobile devices without the need for high-end server infrastructure.[16] This democratization of AI technology is particularly beneficial for small-scale farmers in developing regions, providing them with expert-level diagnostic tools in their pockets.[46]

F. *Metabolic Engineering and Specialized Metabolite Production*

AI is playing an increasingly critical role in plant synthetic biology, particularly in the production of high-value specialized metabolites.[48] Plants produce a diverse array of bioactive compounds, such as the anti-cancer drug vinblastine and the anti-malarial artemisinin, which are often difficult to synthesize chemically.[49] AI models are used to identify biosynthetic pathways and predict metabolic bottlenecks in heterologous systems.[49] For instance, machine learning algorithms can analyze the effects of multi-gene expressions on metabolite accumulation, optimizing the production of compounds like glucoraphanin and cannabinoids in chassis organisms like *Nicotiana benthamiana*.[49]

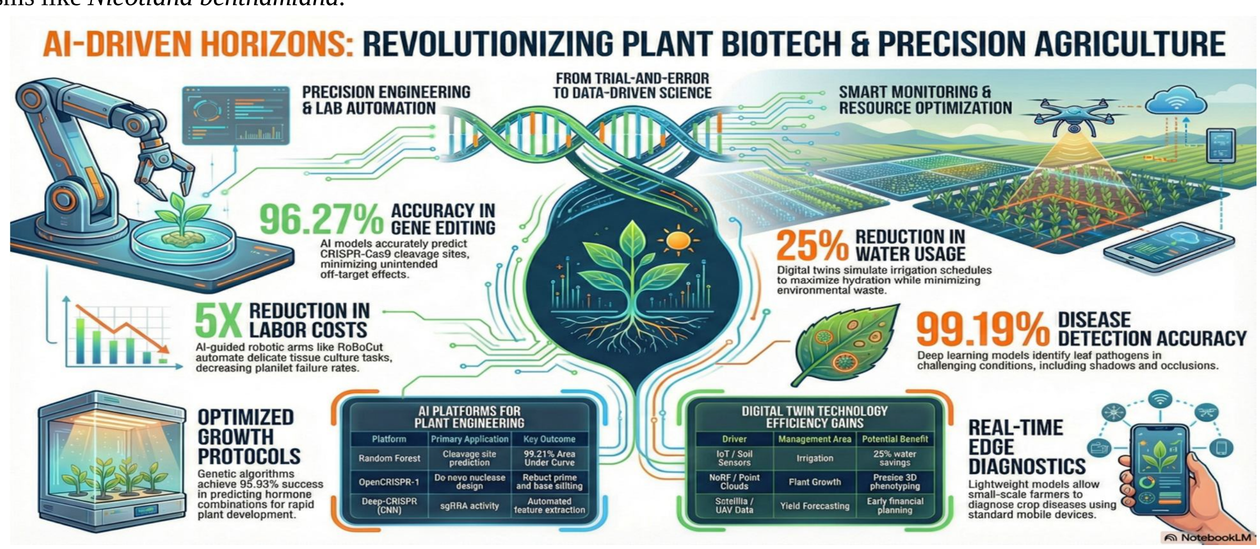

Diagram 4 –AI for Precision Agriculture.

Synthetic biology is also being applied to the energy sector, where AI-driven strain optimization is enhancing the production of next-generation biofuels.[53] Engineered microorganisms like *Saccharomyces cerevisiae* and *Yarrowia lipolytica* are optimized for the conversion of lignocellulosic biomass into fermentable sugars and advanced biofuels such as butanol.

Target Compound	Chassis Host	Engineering Strategy	Scientific Outcome
Vinblastine precursors	*N. benthamiana*	Modular MIA pathway	Early precursor accumulation [49]
Artemisinin	*C. morifolium*	Multi-gene expression	Accumulation in ornamentals [49]
Naringenin	*Y. lipolytica*	Biosensor-aided	8.65 g/L yield [55]
QS-7 (Saponin)	*N. benthamiana*	19-gene transient exp.	Scalable vaccine adjuvant [49]
β-Carotene	*Y. lipolytica*	Genome editing	3,968 mg/L yield [55]

Table 3. – Engineering Strategies of AI in various as results various outcome.

G. The Indian Plant Biotechnology and AI Ecosystem

India is rapidly establishing itself as a global leader in the intersection of AI and biotechnology.[7] The national bioeconomy has seen a 16-fold increase over the past decade, reaching $165.7 billion in 2024, with projections of $300 billion by 2030.[8] This growth is supported by government initiatives like the BioE3 policy and the IndiaAI mission, which foster collaboration between research institutions and the private sector.[8] Indian startup ecosystem is particularly vibrant, with nearly 11,000 biotech startups active by 2025.[9] Companies like Cropin, DeHaat, and Fasal are leveraging AI to provide precision farming solutions to millions of farmers.[57] Cropin, for instance, has digitized 30 million acres of farmland globally and uses AI to provide predictive intelligence for over 10,000 yield varieties.[58] Meanwhile, institutional research at the ICAR-National Institute of Plant Biotechnology (NIPB) and various IISERs is focused on developing climate-resilient crop varieties through genome editing.[59]

Recent policy changes have also streamlined the regulatory landscape for gene-edited crops in India. The "Guidelines on Genetically Engineered Plants Containing Stacked Events, 2025" provide a framework for biosafety assessment, ensuring the safe deployment of agricultural innovations.[8] Additionally, the establishment of the National Biofoundry Network aims to strengthen indigenous biomanufacturing capabilities, accelerating the commercialization of AI-driven biotechnologies.[8]

IV. DISCUSSION

The integration of Artificial Intelligence into plant biotechnology represents a transformative shift that extends beyond simple automation, fundamentally altering the methodologies of genetic improvement and resource management. The results presented in this report highlight the capacity of AI to address long-standing biological bottlenecks through predictive modeling, high-throughput data processing, and autonomous systems. However, the full realization of this potential requires a nuanced understanding of the emerging technical, regulatory, and ethical landscapes.

A. The Paradigm Shift: From Empirical to Prescriptive Agriculture

The transition to "intelligent design" breeding is perhaps the most significant conceptual change in modern agriculture.[5] By moving from the selection of random mutations to the targeted de novo design of proteins and genomic sequences, AI allows for the engineering of traits that go beyond the limitations of natural variation.[1] This is particularly evident in the development of AI-designed nucleases, which allow for "surgical" interventions in the genome with predictable outcomes.[17] The implications for climate resilience are profound; for instance, the ability to rapidly develop salt-tolerant or heat-resistant cultivars through AI-guided "de novo domestication" of wild species could secure food supplies in regions most affected by global warming.[1]

B. The Role of Explainable AI (XAI) in Plant Science

As deep learning models become more prevalent in biotechnology, the demand for transparency and interpretability has intensified.[20] The "black box" nature of complex neural networks can hinder scientific discovery by providing accurate predictions without revealing the underlying biological mechanisms.[20] Explainable AI (XAI) is therefore becoming an essential component of the biotechnological toolkit, allowing researchers to validate model decisions and gain insights into molecular interactions.[20] In the context of multi-omics integration, XAI helps clinicians and researchers understand how various layers of biological information-such as transcriptomics and metabolomics-contribute to a specific phenotype.[20] This is critical for building trustworthy AI systems that can be utilized in both academic research and regulatory submissions.[21] By providing clear, interpretable insights, XAI facilitates the transition from data-driven correlation to mechanism-driven causation, which is the hallmark of rigorous biological science.[10]

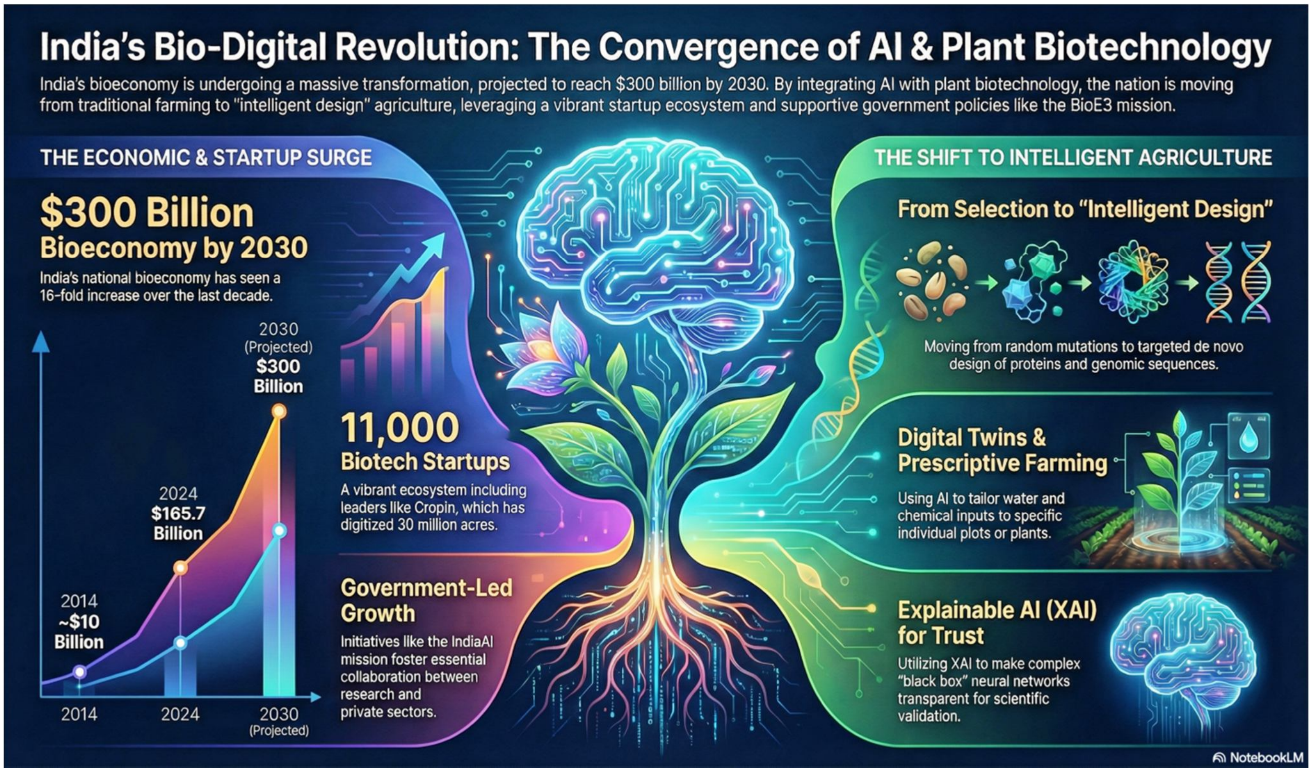

Diagram 4 – India's AI revolution in Plant Biotechnology.

C. Regulatory and Environmental Challenges of AI-Designed Plants

Despite the immense promise of AI-driven biotechnology, the introduction of AI-designed and gene-edited organisms into the environment poses significant regulatory challenges.[18] NGT Category 1 plants, while subject to fewer restrictions in some jurisdictions, still require comprehensive risk assessments to prevent unintended ecological consequences.[64] The possibility of gene flow between gene-edited crops and wild relatives, the potential for pest resistance, and the long-term impacts on soil microbiomes are all areas that require ongoing research and monitoring.[64] AI itself may provide the solution to these regulatory hurdles. Predictive modeling can be used to simulate the environmental impact of new varieties before their release, identifying potential "tipping points" in ecosystem functions.[18] Moreover, AI-powered monitoring systems can track the performance and spread of gene-edited crops in real-time, providing an additional layer of biosafety oversight.[11] The integration of AI into the regulatory framework is therefore a strategic imperative to ensure the responsible and safe use of advanced biotechnologies.[18]

D. Economic Implications and Global Competitiveness

The rapid growth of the Indian bioeconomy serves as a case study for the economic impact of AI-biotech convergence.[8] The proliferation of agritech startups and the substantial increase in venture capital funding indicate that the market recognizes the transformative potential of these technologies.[7] For developing nations, the democratization of AI through lightweight, mobile-based diagnostic tools and accessible genomic databases is crucial for closing the productivity gap.[16]

Collaboration between international research institutions, government bodies, and private entrepreneurs will be essential to foster an ecosystem where high-tech solutions can be implemented at the grassroots level.[39]

V. CONCLUSIONS

The synthesis of Artificial Intelligence and plant biotechnology has inaugurated a new era of agricultural innovation, characterized by predictive precision and sustainable productivity. The findings of this report demonstrate that AI is no longer a peripheral tool but a central component of the biotechnological workflow, driving advancements in genome editing, tissue culture, and field management. The establishment of the "Design-Build-Test-Learn" cycle and the deployment of digital twin technology are shortening breeding cycles and optimizing resource utilization in ways that were previously unimaginable. In conclusion, while the challenges of climate change and food security are formidable, the convergence of AI and plant biotechnology provides a robust toolkit for building a resilient and sustainable future. By leveraging AI to understand and engineer the complexities of plant life, the global community can ensure a secure food supply and a healthier planet for generations to come.

REFERENCES

[1] Integrated biotechnological and artificial intelligence innovations for plant improvement - PMC, accessed February 18, 2026, https://pmc.ncbi.nlm.nih.gov/articles/PMC12740008/
[2] Integrated biotechnological and artificial intelligence innovations for plant improvement - Frontiers, accessed February 18, 2026, https://www.frontiersin.org/journals/plant-science/articles/10.3389/fpls.2025.1736707/full
[3] Using supervised machine-learning approaches to understand abiotic stress tolerance and design resilient crops - PMC, accessed February 18, 2026, https://pmc.ncbi.nlm.nih.gov/articles/PMC12121380/
[4] File 1 - OPEN PEER REVIEW, accessed February 18, 2026, https://files.sdiarticle5.com/wp-content/uploads/2025/07/2025_JABB_132975.docx
[5] AI Powered Plant Breeding - Agri Articles (E-Magazine) 05(03) 2025, accessed February 18, 2026, https://agriarticles.com/wp-content/uploads/2025/06/E-05-03-335-1186-1191.pdf
[6] Next-generation genomics in plant breeding: Integrating genomic selection, high-throughput phenotyping, and gene editing - International Journal of Advanced Biochemistry Research, accessed February 18, 2026, https://www.biochemjournal.com/archives/2025/vol9issue7S/PartB/S-9-7-19-729.pdf
[7] Top AI Startups India 2025 - AI Funding Tracker, accessed February 18, 2026, https://aifundingtracker.com/top-ai-startups-india/
[8] Achievements of Department of Biotechnology- Year Ender 2025 - PIB, accessed February 18, 2026, https://www.pib.gov.in/PressReleasePage.aspx?PRID=2204756
[9] Biotechnology In India, Biotech Companies In India - Ibef.Org, accessed February 18, 2026, https://www.ibef.org/industry/biotechnology-india
[10] Advancing CRISPR with deep learning: A comprehensive review of ..., accessed February 18, 2026, https://pmc.ncbi.nlm.nih.gov/articles/PMC12476096/
[11] Types Of Precision Agriculture Technology 2025 Trends - Farmonaut, accessed February 18, 2026, https://farmonaut.com/precision-farming/types-of-precision-agriculture-technology-2025-trends
[12] Agronomy | Special Issue : Digital Twins in Precision Agriculture - MDPI, accessed February 18, 2026, https://www.mdpi.com/journal/agronomy/special_issues/918898X995
[13] Machine learning in the estimation of CRISPR-Cas9 cleavage sites for plant system - PMC, accessed February 18, 2026, https://pmc.ncbi.nlm.nih.gov/articles/PMC9868961/
[14] A Review on the Detection of Plant Disease Using Machine Learning and Deep Learning Approaches - MDPI, accessed February 18, 2026, https://www.mdpi.com/2313-433X/11/10/326
[15] Application of Artificial Intelligence Technology in Plant MicroRNA Research: Progress, Challenges, and Prospects - PubMed, accessed February 18, 2026, https://pubmed.ncbi.nlm.nih.gov/41465283/
[16] Leveraging deep learning for plant disease and pest ... - Frontiers, accessed February 18, 2026, https://www.frontiersin.org/journals/plant-science/articles/10.3389/fpls.2025.1538163/full
[17] Generative AI is shaping the future of plant gene editing - Genetic Literacy Project, accessed February 18, 2026, https://geneticliteracyproject.org/2025/11/03/generative-ai-is-shaping-the-future-of-plant-gene-editing/
[18] Convergence of CRISPR with Artificial Intelligence (AI): The Rise of Intelligent Gene Editing in Plants - Frontiers, accessed February 18, 2026, https://www.frontiersin.org/research-topics/67273/convergence-of-crispr-with-artificial-intelligence-ai-the-rise-of-intelligent-gene-editing-in-plants
[19] Machine learning and deep learning for genomic data: a data-centric approach to CRISPR/Cas9 gene editing - ResearchGate, accessed February 18, 2026, https://www.researchgate.net/publication/390843609_Machine_learning_and_deep_learning_for_genomic_data_a_data-centric_approach_to_CRISPRCas9_gene_editing
[20] Demystifying the black box: A survey on explainable artificial intelligence (XAI) in bioinformatics - PMC, accessed February 18, 2026, https://pmc.ncbi.nlm.nih.gov/articles/PMC11782883/
[21] Demystifying the Black Box: A Survey on Explainable Artificial Intelligence (XAI) in Bioinformatics - ResearchGate, accessed February 18, 2026, https://www.researchgate.net/publication/387915094_Demystifying_the_Black_Box_A_Survey_on_Explainable_Artificial_Intelligence_XAI_in_Bioinformatics
[22] [2410.11910] Explainable AI Methods for Multi-Omics Analysis: A Survey - arXiv, accessed February 18, 2026, https://arxiv.org/abs/2410.11910
[23] An overview and metanalysis of machine and deep learning-based CRISPR gRNA design tools - PMC, accessed February 18, 2026, https://pmc.ncbi.nlm.nih.gov/articles/PMC6948960/
[24] AI-designed nuclease performs robust knock out, base editing and prime editing in plants, accessed February 18, 2026, https://www.biorxiv.org/content/10.64898/2026.01.20.700739v1

[25] AI-driven advances in plant biotechnology: sharpening the edge of plant tissue culture and genome editing - PubMed, accessed February 18, 2026, https://pubmed.ncbi.nlm.nih.gov/41451278
[26] AI-driven advances in plant biotechnology: sharpening the edge of plant tissue culture and genome editing - Frontiers, accessed February 18, 2026, https://www.frontiersin.org/journals/plant-science/articles/10.3389/fpls.2025.1718810/full
[27] AI-driven advances in plant biotechnology: sharpening the edge of plant tissue culture and genome editing - PMC, accessed February 18, 2026, https://pmc.ncbi.nlm.nih.gov/articles/PMC12727986/
[28] The Technological Trifecta: How Automation, AI, and CRISPR are Forging the Future of Plant Science, accessed February 18, 2026, https://plantcelltechnology.com/blogs/blog/the-technological-trifecta-how-automation-ai-and-crispr-are-forging-the-future-of-plant-science
[29] "Revolutionizing Plant Tissue Culture Through Artificial Intelligence And Data-Driven Technologies" - IJCRT.org, accessed February 18, 2026, https://www.ijcrt.org/papers/IJCRTBJ02015.pdf
[30] The Future of Plant Tissue Culture: Inside the Rise of Automation and Robotics, accessed February 18, 2026, https://plantcelltechnology.com/blogs/blog/the-future-of-plant-tissue-culture-inside-the-rise-of-automation-and-robotics
[31] Artificial Intelligence (AI) in Detection of Abiotic Stress in Plants: A ..., accessed February 18, 2026, https://www.mdpi.com/1424-8220/26/4/1122
[32] (PDF) Artificial Intelligence (AI) in Detection of Abiotic Stress in Plants: A Review, accessed February 18, 2026, https://www.researchgate.net/publication/400593669_Artificial_Intelligence_AI_in_Detection_of_Abiotic_Stress_in_Plants_A_Review
[33] Precision agriculture new frontier: Crop digital twins - AgriLife Today, accessed February 18, 2026, https://agrilifetoday.tamu.edu/2025/01/09/crop-farmers-production-digital-twins/
[34] Digital Twin Technology in Agriculture Powers a Sustainable Future - ICL Group, accessed February 18, 2026, https://www.icl-group.com/blog/digital-twin-technology-agriculture-sustainable-future/
[35] Digital twin-based applications in crop monitoring - PMC - NIH, accessed February 18, 2026, https://pmc.ncbi.nlm.nih.gov/articles/PMC11795032/
[36] Application of Digital Twin Technology in Smart Agriculture: A Bibliometric Review - Preprints.org, accessed February 18, 2026, https://www.preprints.org/manuscript/202507.1502/download/final_file
[37] (PDF) Plant Digital Twins: The Fusion of Biology and Artificial Intelligence - ResearchGate, accessed February 18, 2026, https://www.researchgate.net/publication/399491757_Plant_Digital_Twins_The_Fusion_of_Biology_and_Artificial_Intelligence
[38] Engineers using 'digital twins' to improve agriculture, health, manufacturing and more, accessed February 18, 2026, https://trac-ai.iastate.edu/2025/04/09/engineers-using-digital-twins-to-improve-agriculture-health-manufacturing-and-more/uncategorized/
[39] Insider Analysis of 5 Ag Tech Trends for 2025 - Growing Produce, accessed February 18, 2026, https://www.growingproduce.com/vegetables/insider-analysis-of-5-ag-tech-trends-for-2025/
[40] Application of Digital Twin Technology in Smart Agriculture: A Bibliometric Review - MDPI, accessed February 18, 2026, https://www.mdpi.com/2077-0472/15/17/1799
[41] Global Impact Series: AI-Powered Agriculture: Unlocking New Possibilities for Farmers, accessed February 18, 2026, https://thriveagrifood.com/articles/ai-powered-agriculture-unlocking-new-possibilities-for-farmers/
[42] Agriculture Technology News 2025: New Tech & AI Advances - Farmonaut, accessed February 18, 2026, https://farmonaut.com/news/agriculture-technology-news-2025-new-tech-ai-advances
[43] An advanced deep learning models-based plant disease detection: A review of recent research - Frontiers, accessed February 18, 2026, https://www.frontiersin.org/journals/plant-science/articles/10.3389/fpls.2023.1158933/full
[44] Advances in Deep Learning Applications for Plant Disease and Pest Detection: A Review, accessed February 18, 2026, https://www.mdpi.com/2072-4292/17/4/698
[45] Leveraging deep learning for plant disease and pest detection: a comprehensive review and future directions - PMC, accessed February 18, 2026, https://pmc.ncbi.nlm.nih.gov/articles/PMC11885274/
[46] Agriculture Innovation Fund: Latest Innovations in India for 2025 - Farmonaut, accessed February 18, 2026, https://farmonaut.com/asia/agriculture-innovation-fund-latest-innovations-in-india
[47] 4 Agricultural Tech Startups in India - The Borgen Project, accessed February 18, 2026, https://borgenproject.org/agricultural-tech-startups-in-india/
[48] Applications of artificial intelligence and machine learning in dynamic pathway engineering | Biochemical Society Transactions | Portland Press, accessed February 18, 2026, https://portlandpress.com/biochemsoctrans/article/51/5/1871/233483/Applications-of-artificial-intelligence-and
[49] Plant synthetic biology: from knowledge to biomolecules - PMC, accessed February 18, 2026, https://pmc.ncbi.nlm.nih.gov/articles/PMC12602438/
[50] How Machine Learning is Transforming Metabolic Pathway Design - Patsnap Synapse, accessed February 18, 2026, https://synapse.patsnap.com/article/how-machine-learning-is-transforming-metabolic-pathway-design
[51] Evolution-aided engineering of plant specialized metabolism - PMC - NIH, accessed February 18, 2026, https://pmc.ncbi.nlm.nih.gov/articles/PMC9590541/
[52] Unraveling the specialized metabolic pathways in medicinal plant genomes: a review, accessed February 18, 2026, https://www.frontiersin.org/journals/plant-science/articles/10.3389/fpls.2024.1459533/full
[53] Synthetic biology and metabolic engineering paving the way for sustainable next-gen biofuels: a comprehensive review - Energy Advances (RSC Publishing), accessed February 18, 2026, https://pubs.rsc.org/en/content/articlelanding/2025/ya/d5ya00118h
[54] (PDF) Synthetic biology and metabolic engineering paving the way for sustainable next-gen biofuels: a comprehensive review - ResearchGate, accessed February 18, 2026, https://www.researchgate.net/publication/394764387_Synthetic_biology_and_metabolic_engineering_paving_the_way_for_sustainable_next-gen_biofuels_a_comprehensive_review
[55] Advanced applications of synthetic biology technology in biosynthesis of bioactive compounds from medicinal plants - PMC, accessed February 18, 2026, https://pmc.ncbi.nlm.nih.gov/articles/PMC12828132/
[56] India Deep Tech Alliance Issues Inaugural Report Showing AI Funding Jumps 58% in 2025, Fast-Tracks $1B USD Investment to AI Startup Funding - PR Newswire, accessed February 18, 2026, https://www.prnewswire.com/in/news-releases/india-deep-tech-alliance-issues-inaugural-report-showing-ai-funding-jumps-58-in-2025-fast-tracks-1b-usd-investment-to-ai-startup-funding-302689246.html

[57] Top Companies Leveraging AI to Transform Indian Agriculture - Salam Kisan, accessed February 18, 2026, https://www.salamkisan.com/news/ai-agriculture-startups-top-companies-leveraging-ai-to-transform-indian-agriculture

[58] 6 Agritech startups leading the charge in modernizing India's agricultural ecosystem, accessed February 18, 2026, https://biovoicenews.com/6-agritech-startups-leading-the-charge-in-modernizing-indias-agricultural-ecosystem/

[59] ICAR-NIPB - National Institute of Plant Biotechnology, accessed February 18, 2026, https://www.nipb.res.in/

[60] ICAR EFC - Enhancing climate resilience and ensuring food security with Genome Editing Tools., accessed February 18, 2026, https://icargenomeediting.in/about_the_project.php

[61] A review of artificial intelligence-assisted omics techniques in plant defense: current trends and future directions - Frontiers, accessed February 18, 2026, https://www.frontiersin.org/journals/plant-science/articles/10.3389/fpls.2024.1292054/full

[62] AI in Agriculture — The Future of Farming - Intellias, accessed February 18, 2026, https://intellias.com/artificial-intelligence-in-agriculture/

[63] (PDF) The Integration of Artificial Intelligence in Agriculture: Emerging Trends, Benefits and Challenges - ResearchGate, accessed February 18, 2026, https://www.researchgate.net/publication/390905953_The_Integration_of_Artificial_Intelligence_in_Agriculture_Emerging_Trends_Benefits_and_Challenges

[64] Combining AI and new genomic techniques to 'fine-tune' plants: challenges in risk assessment - PMC, accessed February 18, 2026, https://pmc.ncbi.nlm.nih.gov/articles/PMC12528024/