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AI-Driven Nutrigenomics: Engineering Climate-Resilient Biofortified Crops for India's Nutrition Security

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Abstract

AI-driven nutrigenomics involves artificial intelligence to genetic analysis to improve human nutrition and agricultural productivity. By integrating genomics, nutrition science, and AI technologies, it helps identify genetic factors that influence nutrient absorption and metabolism. This approach supports personalised nutrition strategies, enhances the biofortification of staple crops, and accelerates the development of nutrient-dense, climate-resilient crop varieties. More than 150 biofortified crop cultivars of cereals, pulses, and oilseeds have been developed as a result of extensive research conducted by the National Agricultural Research Education and Extension System (NAREES), which is led by the Indian Council of Agricultural Research (ICAR) and involves State Agricultural Universities (SAUs) and Central Universities (CUs). India faces a major micronutrient challenge, with nearly 57% of children affected by zinc deficiency and about 35% suffering from iron-deficiency anaemia, and these nutritional concerns may be further aggravated by climate change, which threatens food security through declining crop yields and increased heat stress. In this context, AI-enabled nutrigenomics offers a promising solution by combining genomic selection, multi-omics analysis, and advanced gene-editing tools to speed up crop improvement. Successful outcomes include iron-enriched pearl millet (ICTP 8203) and zinc-fortified wheat (HD 3226), both designed to perform well under high-temperature conditions. The adoption of AI-

based methods has significantly reduced the traditional crop breeding timelines from nearly a decade to just two to three years. These advances improve nutritional outcomes, enhance farmer incomes, and promote climate-resilient agriculture. Despite challenges such as limited genomic databases and regulatory barriers, AI-driven nutrigenomics demonstrates strong potential to strengthen nutrition security and support sustainable agricultural development in developing and emerging economies.

Keywords: Nutrigenomics, AI Breeding, Biofortification, Climate Resilient Crops, Sdg 2

Introduction

India has made significant advancements in agricultural production over the past decades, but the improvement in food availability has not been reflected equally in nutritional achievements. Micronutrient deficiencies, especially iron and zinc, are still prevalent and affect children, women, and the economically disadvantaged sections of society. Recent estimates show that approximately 57% of Indian children are zinc-deficient, and about 35% of children are affected by iron-deficiency anaemia, which indicates the extent of hidden hunger in the country (ICMR, 2020; WHO, 2021). The consequences of these deficiencies are severe and affect physical development, intellectual ability, immune systems, and ultimately economic productivity.

The problem of malnutrition is further exacerbated by the issue of climate change, which is increasingly threatening the sustainability of agriculture. Rising temperatures, heat waves, unpredictable rainfall, and deteriorating soil quality are already impacting crop growth in various parts of India. In addition to lowering crop productivity, climate change also impacts the nutritional value of crops by reducing the level and availability of key micronutrients. There is evidence to suggest that increased levels of carbon dioxide in the atmosphere and heat stress can lower the iron and zinc levels in key cereals, thereby increasing the disparity between calorie adequacy and nutritional adequacy (Myers et al., 2014; FAO, 2022).

Biofortification has recently been recognized as a sustainable agricultural approach to overcome micronutrient deficiencies through the biofortification of crops rather than relying on post-harvest fortification. In India, significant progress has been made through collective efforts under NAREES, led by ICAR and State and Central Universities, as indicated in Figure 1. This has resulted in the development of more than 150 biofortified varieties of cereals, pulses, and oilseeds to overcome iron, zinc, and other micronutrient deficiencies (ICAR, 2023). Although this progress is appreciable, the rising rate of climate change requires more rapid approaches to crop improvement.

However, recent breakthroughs in artificial intelligence and genomics have opened new avenues for improving biofortification. AI-based nutrigenomics is the fusion of computational intelligence with genomics and nutritional sciences to discover the genetic basis of nutrient uptake, availability, and utilisation. This transdisciplinary approach has made it possible to improve crops more accurately and quickly, which can be used to develop climate-resilient and nutrient-rich crops according to the nutritional requirements of specific populations. In the context of India's diverse climate and nutritional deficiencies, AI-based nutrigenomics can be a feasible approach to ensure long-term nutrition security (Kaput et al., 2014; Varshney et al., 2021).

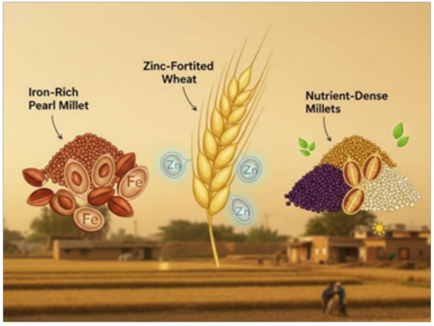

Figure 1 Biofortified Staple Crops Enhancing Micronutrient Availability In Indian Agro-Ecosystem

Review of Literature

Nutrigenomics has received growing attention as a scientific area that investigates the relationship between genetic variation and nutritional response. Initial studies in this area showed that people vary in their metabolic response to the same diet because of genetic differences, thus questioning the efficacy of generalized dietary advice (Kaput et al., 2014). These findings formed the basis for the development of personalised dietary strategies that consider genetic differences in nutrient uptake and metabolism.

Concurrent with the development of nutrigenomics, biofortification has also received considerable attention as an agricultural approach to address micronutrient malnutrition. Findings from worldwide interventions have shown that biofortified crops, such as iron-enriched cereals and zinc-biofortified legumes, are effective in improving micronutrient intake among at-risk groups without the need to alter dietary practices (Bouis and Saltzman, 2017). This makes biofortification an important approach for low- and middle-income countries where micronutrient supplementation programs may be limited by logistical issues.

However, the conventional biofortification approach is hampered by the long breeding cycles and the lack of emphasis on environmental stress factors. Climate change has been identified as a significant constraint, which impacts both the yield and nutritional content of crops, as indicated in Figure 2. According to the study by Myers et al. (2014), higher concentrations of carbon dioxide and heat stress lower the iron and zinc contents in key food crops, thus worsening the problem of hidden hunger even in food-secure areas.

The use of artificial intelligence in crop improvement has been well-documented in the current literature. The studies conducted by Crossa et al. (2017) and Montesinos-López et al. (2018) indicated that the AI-assisted genomic selection models are superior to traditional breeding approaches in predicting the accumulation of micronutrients and stress tolerance. The integration of genomic, phenotypic, and environmental information by AI facilitates more precise selection and significantly shortens the breeding cycles.

The union of AI and nutrigenomics has widened the horizon of nutrition-sensitive agriculture. By combining human nutrigenomic information with nutritional information of crops, agricultural systems can be made more attuned to the nutritional needs of specific populations (Kaput et al., 2014). In the Indian context, where genetic diversity affects iron and zinc metabolism, this combination is crucial for enhancing the efficacy of nutritional interventions (Reddy et al., 2018).

The biofortification programs in India, conducted under ICAR and NAREES, have been well documented, with reports of successful results obtained from varieties such as iron biofortified pearl millet (ICTP 8203) and zinc biofortified wheat (HD 3226). These varieties have shown enhanced nutritional values without compromising yields even under heat stress conditions, thus emphasizing the importance of combining nutrition and heat stress resilience (HarvestPlus, 2020; ICAR, 2023), see Figure 3. However, despite these breakthroughs, there are still challenges, such as the lack of genomic databases, regulatory issues concerning genome editing technology, and inequitable distribution of AI infrastructure. Moreover, issues concerning the ethics of data regulation and technology distribution add to the complexities of widespread adoption (Klerkx et al., 2019; WHO, 2021). In general, it can be seen from the literature that, although nutrigenomics, AI-assisted breeding, and biofortification have shown great promise individually, their combined use has not been adequately explored, especially in developing nations.

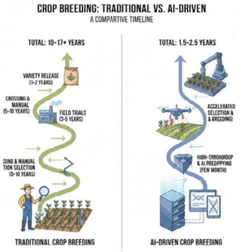

Figure 2 Comparison of traditional And Ai-Driven Crop Breeding Approaches

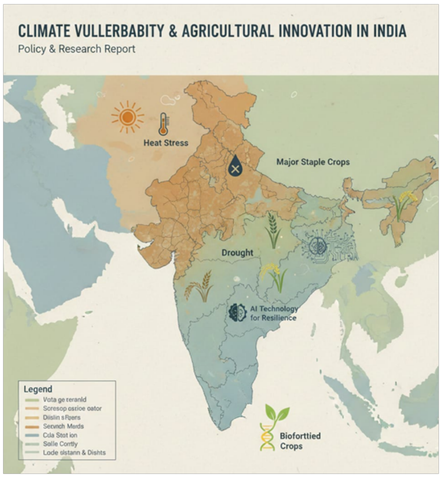

Figure 3 Climate Vulnerability And Ai-Driven Agriculture Innovation Across India.

Artificial Intelligence in Crop Genomics and Breeding

Artificial intelligence has come to be recognized as a revolutionary aid in contemporary crop improvement, as it allows for the evaluation of large and complex data sets produced through genomic sequencing, phenotyping platforms, and environmental monitoring systems. Conventional breeding methods are highly dependent on multi-year field testing and phenotypic selection, which are protracted and often inadequate for dealing with complex traits such as climate resilience and micronutrient accumulation. AI-based models have been able to circumvent these challenges by combining genomic, phenotypic, and climatic data to predict crop performance with greater accuracy and rapidity (Crossa et al., 2017).

Machine learning algorithms have been increasingly employed to detect genetic markers linked to heat tolerance, drought resistance, and nutrient stability. Through the simulation of crop performance in various climate conditions, AI allows breeders to choose genotypes that are likely to perform better in future climate conditions. In the Indian scenario, where rising temperatures and unpredictable rainfall patterns pose a threat to major crops, such predictive capacities are extremely useful. AI-based genomic selection has greatly diminished the uncertainty involved in breeding for climate resilience while simultaneously preserving nutritional quality (Montesinos-López et al., 2018; Varshney et al., 2021).

AI-Enabled Biofortification Strategies

Biofortification is the process of enhancing the micronutrient levels in crops using genetic approaches. Although traditional biofortification projects have shown significant success, their efficiency is often limited by factors such as long breeding times and environmental factors. AI-based biofortification represents an innovative and adaptive strategy that uses gene-nutrient information to predict gene stability in stressed environments, as shown in Figure 4.

The combination of multi-omics platforms such as genomics, transcriptomics, proteomics, and metabolomics using AI models enables the identification of regulatory networks that control nutrient accumulation and bioavailability. AI-based biofortification has enabled the development of iron biofortified pearl millet and zinc biofortified wheat that maintain their nutritional quality even under high temperature stress conditions in India. This represents an effective strategy to address malnutrition and climate change simultaneously (Bouis and Saltzman, 2017; ICAR, 2023).

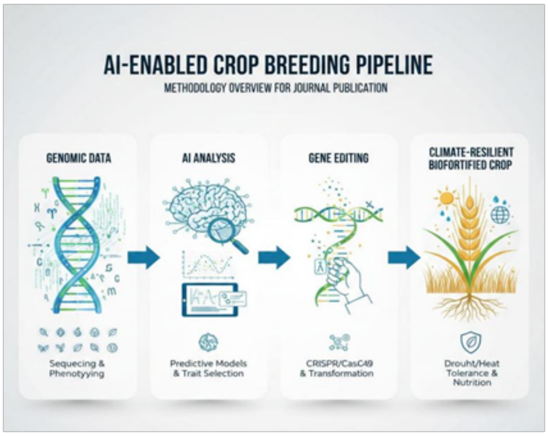

Figure 4 AI-enabled Crop Breeding Pipeline For Developing Climate-Resilient Biofortified Varieties

Nutrigenomics and Population-Specific Nutrition

Nutrigenomics has improved the understanding of the impact of genetic diversity on nutrient metabolism and health. Indian populations have been found to have high genetic diversity, which has been attributed to the differences in micronutrient requirements and metabolism. Genetic polymorphisms have been found to affect iron absorption and zinc metabolism, contributing to the high prevalence of anaemia and micronutrient deficiencies in the country (Reddy et al., 2018).

AI-assisted nutrigenomics helps to combine human genetic information with crop nutrient information, which can be used to create population-specific nutrition plans. Instead of using the same approach for all, this approach helps to create crops that provide nutrients in a more bioavailable form for a particular population. This convergence of agricultural production and human nutritional needs is a major step forward in nutrition-sensitive agriculture and improves the efficacy of biofortification interventions (Kaput et al., 2014; WHO, 2021), refer to Figure 5.

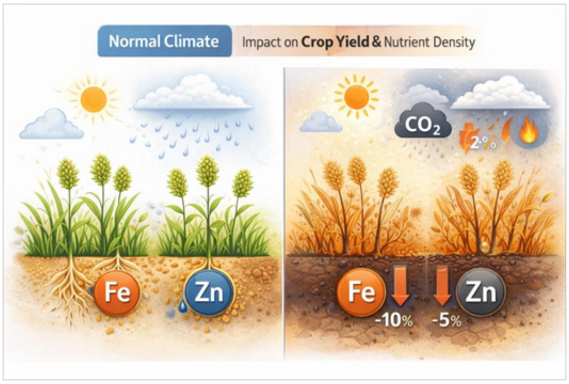

Figure 5 Impact of Climate Change on Crop Yield and Micronutrient Density

Decision Support Systems and Digital Agriculture

The convergence of nutrigenomics with AI in digital agriculture has resulted in the creation of sophisticated decision support systems that help breeders, farmers, and policymakers. These decision support systems process real-time information on soil health, climatic conditions, crop genetics, and nutritional needs to help make decisions on crop selection and management.

For farmers, AI decision support systems help make decisions on the type of crops to be grown based on the climatic conditions and nutritional needs. For scientists and policymakers, these systems help analyse scenarios to improve food and nutrition security. In the Indian agricultural setting, the use of digital decision support systems can help close the gap between scientific innovation and implementation, ensuring that nutrigenomics innovations are converted into practical gains (Klerkx et al., 2019).

Socio-Economic and Institutional Implications

The use of AI nutrigenomics has applications that not only lie in scientific innovation but also in the creation of socio-economic value. Nutrient-rich and climate-resilient crops are less risky in production for farmers, and they improve the stability of crop yields. For consumers, improved nutrition leads to better health, which in turn reduces healthcare costs and improves productivity.

Institutional support has been critical in the advancement of biofortification and nutrigenomics in India. Collective efforts by ICAR and NAREES have ensured the development and scaling of biofortified crops through partnerships with State Agricultural Universities. However, factors such as lack of access to AI infrastructure, disparities in technological capacity, and regulatory ambiguities surrounding genome editing technologies are some of the challenges that still hinder widespread adoption (ICAR, 2023; WHO, 2021).

Advantages

Strengthening Nutritional Outcomes through Precision Crop Improvement

The application of AI in crop science research helps to conduct a thorough analysis of both genetic information and visible plant traits, making it possible to identify genetic signals associated with priority micronutrients like iron, zinc, and provitamin A. This is an improvement in the precision of crop variety selection with reliable nutritional properties. Therefore, nutrient-fortified staple foods, such as zinc-improved wheat and iron-enriched rice, can contribute significantly to the alleviation of micronutrient deficiencies in at-risk groups without necessarily changing long-established food habits.

Integrating Nutrition with Climate Adaptation

Biofortified crop varieties, especially those derived from millets and wheat, are being developed to resist environmental stresses like heat, drought, and poor soil. By breeding and improving these crops, they remain productive and nutritious even when the climatic conditions are adverse. This convergence of nutritional improvement and stress resistance is helpful in ensuring food and nutrition security in the face of increasing climate stresses.

Accelerated Crop Development and Cost Efficiency

Using predictive models based on artificial intelligence, plant breeders can now identify potential plant lines at very early stages of growth, thus cutting down on the time it used to take to develop better plant varieties. This helps reduce research costs and allows faster access to improved seeds by farming communities.

Evidence-Based Agricultural Planning

Through the use of predictive modelling, scientists and agronomists can predict the performance of new crop varieties under different environmental conditions. This is a predictive tool that improves climate adaptation strategies and helps in planning for the breeding and growth of new crop varieties.

Supporting Farmers and Sustainable Resource Use

Stress-resistant and nutritious crops provide farmers with higher yield assurance, even in unfavorable environments, and thus contribute to stabilizing their incomes and preventing crop failures. Higher yield stability also reduces dependence on intensive inputs such as irrigation and chemical fertilizer, which reduces production costs and environmental degradation. Additionally, nutritious crops reduce dependence on external nutritional supplements, while AI-driven agronomic advice promotes more efficient and sustainable input use.

Disadvantages

Challenges in Farmer Uptake

The adoption of biofortified crop varieties remains constrained in many marginal and rain-dependent farming regions due to limited outreach services, inadequate farmer training, and insufficient seed distribution mechanisms. Consumer acceptance can also be influenced by preferences, particularly when newly introduced varieties differ from traditional crops in flavour, texture, or cooking behaviour. For small-scale farmers, hesitation often stems from uncertainty about economic returns and concerns over the risks associated with replacing well-known crop varieties in the absence of on-farm proof of advantage.

Constraints Related to Nutrition and Policy

The nutritional benefits provided by biofortified crops are not always uniform, as factors such as soil health, cultivation practices, storage conditions, and food preparation techniques can affect how nutrients are retained and absorbed. These variations may reduce health outcomes and complicate efforts to evaluate the efficacy of biofortification programs within public nutrition programs.

Ethical and Regulatory Challenges

The incorporation of artificial intelligence and genome-editing technologies into agricultural systems presents ethical, bio-safety, and societal acceptability issues. Regulatory decisions may be influenced by public concerns about long-term safety, environmental impact, and transparency, especially in areas that continue to take a cautious stance toward genetically modified or edited crops. Clear governance frameworks and inclusive communication between scientists, decision-makers, and the general public are necessary to address these issues.

Infrastructure and Technical Limitations

Developing artificial intelligence within crop breeding systems requires access to digital infrastructure, including reliable data management systems, high-performing computers, and modern phenotyping facilities. These demands often exceed the financial and technical capabilities of smaller or locally focused research institutions. Moreover, differences in data reliability, gaps in datasets, and inconsistencies in data quality can undermine predictive accuracy and lower confidence in AI-based trait selection outcomes.

Challenges and Future Research Directions

Despite its potential, AI-driven nutrigenomics has a number of issues that need to be resolved. The performance of AI models is limited by the scarcity of high-quality genomic and phenotypic datasets, especially for understudied crops. Widespread adoption is also hampered by ethical and legal issues with data ownership, privacy, and public acceptance of genome-edited crops. Expanding genomic databases, enhancing model transparency, and fostering interdisciplinary cooperation among data scientists, nutritionists, and agricultural scientists should be the main goals of future research. To guarantee inclusive and equitable benefits, there will also need to be a stronger focus on farmer engagement and participatory research. By overcoming these obstacles, AI-driven nutrigenomics will be able to progress from a research-based invention to a scalable nutrition security solution (Klerkx et al., 2019; Varshney et al., 2021).

Government-Led Initiatives Supporting Climate-Resilient Biofortified Crops in India

Alongside rapid advances in AI-driven nutrigenomics, the Government of India has taken proactive steps to strengthen both nutrition security and climate-resilient agriculture by promoting the large-scale development and release of improved crop varieties. A recent milestone in this effort was the release of 109 high-yielding, climate-resilient, and biofortified crop varieties across 61 crops at the Indian Agricultural Research Institute in New Delhi, highlighting the country's strong commitment to science-based agricultural transformation. The Indian Council of Agricultural Research led the charge, working closely with State Agricultural Universities and Krishi Vigyan Kendras. These new crops are designed not only to survive heat, drought, and erratic weather, but also to deliver improved nutrition. The "lab-to-land" approach focuses on giving farmers seeds that can handle tough conditions, cost less to grow, and boost incomes by bringing better harvests, while also encouraging the growth and consumption of more nutrient-rich crops.

India's policy and research commitments reinforce the potential of science-driven approaches like AI-powered nutrigenomics to boost nutrition and make farming more climate-resilient. The lineup of 109 newly released varieties covers cereals, millets, pulses, oilseeds, and horticultural crops, each built to handle harsh weather and deliver better nutrition. The integration of strong research and hands-on institutional support is helping India build food systems that can handle climate change and close the gap on micronutrient deficiencies, especially as diets and the environment keep shifting (Press Information Bureau, 2024).

Conclusion

AI-driven nutrigenomics is changing the way we tackle big problems like malnutrition, climate change, and the future of farming. When artificial intelligence, crop genetics, and nutrition science are brought together, developing crops that are both more nutritious and resilient to changing climates becomes faster and more precise. Researchers in India have already rolled out iron-rich pearl millet and zinc-enriched wheat, demonstrating that this combination of technology and science delivers real results. Challenges remain, including the need for comprehensive genomic data, clearer regulatory frameworks, and more equitable access to technology. However, with sustained government support and continued investment in AI and genomics, these advances can achieve significant impact. As climate change intensifies, AI-driven nutrigenomics offers India and similarly positioned nations a credible pathway to building food systems that are both nutritionally robust and climate-resilient (Bouis and Saltzman, 2017; Varshney et al., 2021).

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