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Synthetic Biology in Crop Breeding: Designing Smarter Plants for a Changing World

*Akash Gaurav, Shoeb Ahmed, Vibha Kumari, Shivam Kumar Jha, Alisha Singh and Kanakratnam Kumari
Department of Genetics and Plant Breeding, Chaudhary Charan Singh University, Meerut 250004, Uttar Pradesh, India
*Corresponding Author's email: akashgaurav64@gmail.com

Synthetic biology is emerging as a powerful approach for modern crop breeding by enabling the planned redesign of genes, gene networks, and metabolic pathways to develop improved crop varieties. Climate change, drought, salinity, pest outbreaks, declining soil fertility, and rising input costs are creating serious challenges for agriculture, particularly in countries such as India. Unlike conventional breeding, which often requires many years, synthetic biology provides faster and more precise strategies for improving stress tolerance, disease resistance, nutrient-use efficiency, yield stability, and nutritional quality. Key technologies such as CRISPR-Cas, base editing, prime editing, synthetic promoters, gene circuits, and metabolic pathway engineering are expanding the possibilities of crop improvement. Their applications include the development of climate-resilient crops, improved yield and productivity, nutritional biofortification, reduced fertilizer and pesticide use, and stronger resistance against pests and diseases. Integration with artificial intelligence, precision agriculture, drones, sensors, and high-throughput phenotyping can further accelerate the identification of useful genes and the evaluation of improved plants under field conditions. For Indian agriculture, synthetic biology can support the development of heat-tolerant wheat, drought-resilient pulses, disease-resistant rice, nutrient-rich millets, improved oilseeds, and vegetables with longer shelf life. Responsible application, supported by safety testing, transparent regulation, environmental assessment, and public awareness, will be essential. Overall, synthetic biology can complement conventional breeding, molecular breeding, field evaluation, and farmers' knowledge to create climate-smart, sustainable, and farmer-friendly crops.

Keywords: Synthetic biology, Crop breeding, Climate-resilient crops, Genome editing, Sustainable agriculture

Introduction

Agriculture is facing one of the most difficult periods in human history. Farmers are expected to produce more food, better nutrition, and stable yields under changing climatic conditions, while using fewer natural resources. Rising temperature, irregular rainfall, drought, salinity, new pest outbreaks, declining soil fertility, and increasing cost of inputs are directly affecting crop production across the world. Major crops such as wheat, rice, maize, pulses, oilseeds, vegetables, fruits, and millets are already facing the pressure of climate change and resource limitation. Traditional breeding has played a historic role in crop improvement, but it often requires many years to develop a new variety. Therefore, crop improvement now requires approaches that are faster, more precise, and better aligned with future agricultural challenges.

Synthetic biology offers such a possibility. Instead of only selecting naturally available variation, scientists can now identify important genes, regulate their activity, improve biological pathways, and develop crops with stronger stress tolerance, better disease resistance, improved nutrient-use efficiency, higher yield stability, and enhanced nutritional quality. When combined with genome editing, molecular breeding, artificial intelligence, and field-based selection, synthetic biology can become an important tool for designing climate-smart and farmer-friendly crops for the future.

What is Synthetic Biology in Crop Breeding?

Synthetic biology involves modifying genes, regulating biological pathways, improving stress-response systems, and designing new functions in plants. It can be used to improve traits such as drought tolerance, heat tolerance, disease resistance, nutrient-use efficiency, yield stability, grain quality, and nutritional value. Conventional breeding depends mainly on crossing two plants and selecting better offspring over several generations. Marker-assisted selection helps breeders identify and transfer useful genes with the help of DNA markers. Genetic modification can introduce a useful gene into a crop plant. Genome editing can change a specific DNA sequence with high precision. Synthetic biology goes one step further by redesigning biological systems, gene networks, and metabolic pathways in a more planned way. This makes it different from simple gene editing because it can improve not only one gene but also the larger biological system controlling a trait. For example, instead of only selecting a drought-tolerant plant, synthetic biology can help identify drought-responsive genes, regulate their expression, improve root development, enhance water-use efficiency, and strengthen stress-defense pathways. In this way, it provides a more complete strategy for crop improvement.

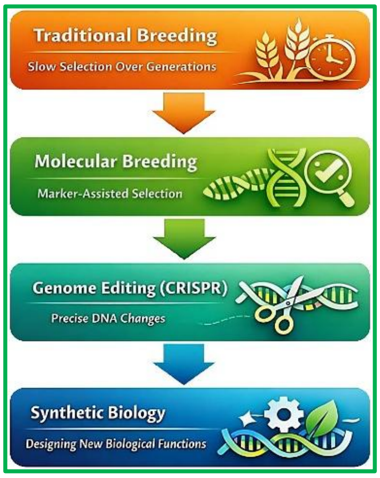

Figure 1: Evolution of Crop Breeding

The Technology Behind Synthetic Biology

CRISPR-Cas technology is one of the most important tools used in synthetic biology. CRISPR works like a molecular scissor that can cut DNA at a specific location and allow scientists to modify a gene. It has already been used in several crops, including rice, wheat, maize, tomato, soybean, and fruits, for improving yield, quality, stress tolerance, disease resistance, and shelf life. However, synthetic biology is broader than CRISPR-Cas9. New tools such as base editing, prime editing, CRISPR activation, CRISPR repression, synthetic promoters, gene circuits, and metabolic pathway engineering are expanding the possibilities of crop improvement. Base editing can make very small and precise changes in DNA. Prime editing can introduce more accurate genetic changes. Synthetic promoters can control when and where a gene should be active. Gene circuits can help plants respond more effectively to stress signals. These tools make crop improvement more accurate, flexible, and future-oriented.

Applications of Synthetic Biology

Designing Climate-Resilient Crops

Synthetic biology can help scientists identify stress-responsive genes and modify them to improve plant survival under difficult conditions. In wheat, terminal heat stress during grain filling reduces grain weight and quality. Synthetic biology can help improve heat tolerance by targeting genes involved in photosynthesis, membrane stability, heat shock proteins, antioxidant activity, and grain development. In rice, genes related to salinity tolerance, drought tolerance, and submergence survival can be improved. In maize and pulses, improved root architecture

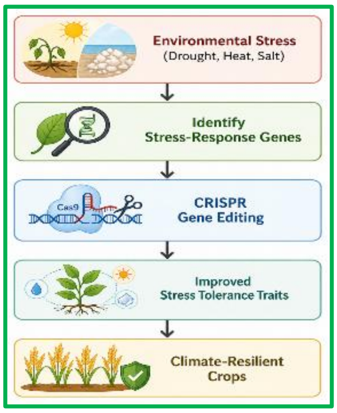

Figure 2: Stress-Resilient Plant Design

and water-use efficiency may help plants perform better under drought conditions. Instead of depending only on external inputs, future crops must have internal biological strength to tolerate stress and maintain productivity.

Improving Yield and Crop Productivity

Synthetic biology can help improve yield by targeting genes and pathways involved in plant architecture, flowering, grain development, photosynthesis, and nutrient transport. In cereals such as wheat, rice, and maize, it can help improve grain number, grain weight, tillering, and biomass production. In pulses, it can help improve seed size, pod number, protein content, and stress tolerance. In horticultural crops, it can support better fruit size, taste, ripening, shelf life, and disease resistance. However, synthetic biology should not replace conventional breeding. The best approach is to combine synthetic biology with field-based selection, molecular breeding, and farmers' feedback. A crop variety is useful only when it performs well under real field conditions.

Nutritional Improvement and Biofortification

Food security is not only about producing more food; it is also about producing nutritious food. Many people suffer from hidden hunger due to deficiency of iron, zinc, vitamin A, protein, and other essential nutrients. Synthetic biology can help improve nutritional quality by modifying metabolic pathways that control nutrient accumulation in edible plant parts. Crops can be improved for higher iron, zinc, provitamin A, essential amino acids, healthy oils, antioxidants, and beneficial pigments. Cereals can be improved for micronutrient density, pulses for protein quality, oilseeds for healthier oil composition, and fruits and vegetables for vitamins, antioxidants, colour, taste, and shelf life. This makes synthetic biology highly important for both agriculture and public health. In India, where malnutrition and micronutrient deficiency remain serious concerns, biofortified crops developed through modern breeding and synthetic biology can support nutritional security. Such crops can provide better health benefits without requiring major changes in food habits.

Reducing Input Use and Supporting Sustainable Farming

One of the most farmer-relevant benefits of synthetic biology is its potential to reduce input use. Crops with strong disease resistance may need fewer pesticide sprays. Plants with better nitrogen-use efficiency may require less fertilizer. Drought-tolerant crops may perform better under limited irrigation. Salt-tolerant crops may allow cultivation in marginal lands affected by salinity. This is very important because excessive use of fertilizers and pesticides increases the cost of cultivation, affects soil health, pollutes water, and reduces biodiversity. Synthetic biology can support the development of low-input and climate-smart crop varieties. Such crops can help farmers reduce production costs and make agriculture more sustainable. For small farmers, even a small reduction in fertilizer, pesticide, or irrigation cost can make a big difference. Therefore, synthetic biology should be directed not only toward high-end scientific goals but also toward practical farmer-level benefits.

Fighting Pests and Diseases

Pests and diseases cause heavy crop losses every year. Fungal, bacterial, viral, and insect-vectored diseases reduce yield and quality in almost all major crops. Synthetic biology provides new ways to strengthen the natural immune system of plants. Scientists can identify resistance genes, activate defense pathways, silence susceptibility genes, and improve the plant's ability to recognize pathogens. For example, instead of only spraying chemicals after disease attack, plants can be developed with stronger internal defense mechanisms. This can reduce crop losses and lower dependence on chemical pesticides. In crops such as rice, wheat, tomato, maize, and vegetables, genome editing has shown potential for improving resistance against important diseases. This approach can make crop protection safer, more precise, and environmentally friendly.

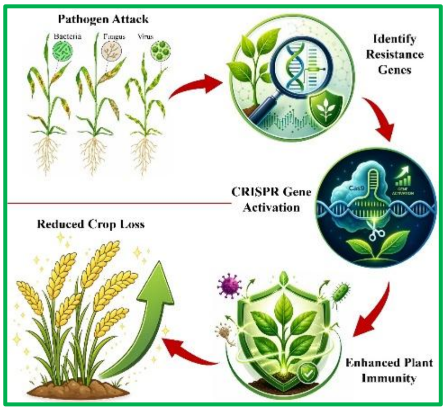

Figure 3: Disease-Resistant Crop Engineering

Integration with Artificial Intelligence and Precision Agriculture

The future of synthetic biology will become stronger when combined with artificial intelligence and precision agriculture. AI can help scientists analyze large genomic datasets, predict gene function, identify better editing targets, and design improved gene combinations. Machine learning can also help predict how a plant may perform under drought, heat, salinity, or disease pressure. When AI is combined with drones, sensors, satellite imaging, climate models, and high-throughput phenotyping, crop breeding can become faster and more accurate. For example, AI can identify important genes for drought tolerance, CRISPR can edit those genes, and field sensors can test plant performance under real conditions. This integration can help develop crop varieties suitable for specific regions such as heat-prone wheat areas, drought-prone pulse-growing regions, saline rice fields, and low-input farming systems.

Importance for Indian Agriculture

India has highly diverse farming conditions. Some regions face terminal heat stress, some face drought, some suffer from salinity, while others are affected by floods, pests, and diseases. Wheat grown in North India often suffers from high temperature during grain filling. Rice faces drought, salinity, submergence, and bacterial diseases in different regions. Pulses are affected by drought, wilt, pod borer, and low productivity. Oilseed crops face disease pressure and quality limitations. Vegetables and fruits suffer from pest attack, short shelf life, and post-harvest losses. Synthetic biology can help address these problems by developing crops that are more resilient, input-efficient, and nutritionally rich. This is especially important for small and marginal farmers, who often cannot afford repeated pesticide sprays, high fertilizer doses, or assured irrigation. If crops are developed with better natural resistance, improved root systems, efficient nutrient uptake, and stress tolerance, farmers can reduce input costs and improve yield stability. For India, synthetic biology should not be seen only as a laboratory science. It should be linked with real agricultural problems such as heat-tolerant wheat, drought-resilient pulses, disease-resistant rice, nutrient-rich millets, improved oilseed quality, and vegetables with longer shelf life.

Regulatory, Ethical, and Public Acceptance Issues

Despite its promise, synthetic biology also faces important challenges. One concern is off-target editing, where unintended changes may occur in the genome. Although modern tools are becoming more accurate, careful testing is still necessary. Another challenge is the delivery of editing tools into plant cells and regeneration of edited plants, especially in crops that are difficult to transform. Regulation is another important issue. Different countries have different rules for genome-edited and genetically modified crops. Public acceptance is also very important because many people still have doubts about advanced genetic technologies. Therefore, safety testing, transparent regulation, environmental risk assessment, and clear public communication are necessary. It is also important to explain that all genome-edited crops are not the same. Some may contain foreign DNA, while others may only have small targeted changes similar to natural mutations. Clear communication will help farmers and consumers understand the difference between scientific innovation and misinformation.

Conclusion

Synthetic biology is reshaping crop breeding by allowing scientists to design plants with improved traits in a precise and planned manner. It has the potential to develop crops that can tolerate climate stress, resist pests and diseases, use nutrients and water more efficiently, and provide better nutritional quality. For India, this technology can become a powerful tool for strengthening food security, nutritional security, and sustainable agriculture. However, synthetic biology should not be viewed as a replacement for traditional breeding or farmer knowledge. It should be used as a supportive technology that works together with conventional breeding, molecular breeding, field evaluation, and farmers' experience. If applied responsibly, synthetic biology can help create a new generation of climate-smart, resource-efficient, and farmer-friendly crops for a changing world.

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