Journal of Advances in Biology & Biotechnology

Volume 27, Issue 8, Page 615-631, 2024; Article no.JABB.119984
ISSN: 2394-1081

Innovative Approaches in Crop Genetic Engineering for Sustainable Agriculture: A Review

Michelle C. Lallawmkimi [a++*], Ashoka. P [b#], D J M S N K Sri Veda [c†], Akash Yadav [d‡], Dhivya. B [e^], Manoj Kumar [f##] and Ankita Rout [g#^]

[a] *Krishi Vigyan Kendra (KVK), Kolasib, Mizoram, India.*
[b] *Agricultural Reaserch Station, Hanumanmatti(p) Ranebennur(tq), Haveri, Karanataka, India.*
[c] *Department of Genetics and Plant Breeding & Seed Science and Technology, Centurion University of Technology and Management, Paralakhemundi, Gajapati, Odisha, India.*
[d] *ICAR - Indian Grassland and Fodder Research Institute, Jhansi Uttar Pradesh, India.*
[e] *College of Agricultural Technology, Theni, India.*
[f] *IARI Regional Station Shimla, Himanchal Pradesh, India.*
[g] *Department of Seed Science and Technology Faculty of Agricultural Sciences, Siksha 'O' Anusandhan (Deemed to be University), Bhubaneswar - 751003. Odisha, India.*

Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

Article Information

DOI: https://doi.org/10.9734/jabb/2024/v27i81177

Open Peer Review History:
This journal follows the Advanced Open Peer Review policy. Identity of the Reviewers, Editor(s) and additional Reviewers, peer review comments, different versions of the manuscript, comments of the editors, etc are available here: https://www.sdiarticle5.com/review-history/119984

Review Article

Received: 20/05/2024
Accepted: 22/07/2024
Published: 29/07/2024

[++] *Senior Scientist and Head;*
[#] *Professor and Head,*
[†] *Assistant Professor;*
[‡] *Senior Research Fellow;*
[^] *Assistant Professor (Agronomy);*
[##] *Senior Technical Assistant;*
[#^] *PhD (Agri) Scholar;*
**Corresponding author: E-mail: michellelawmkimi@gmail.com;*

Cite as: *Lallawmkimi, Michelle C., Ashoka. P, D J M S N K Sri Veda, Akash Yadav, Dhivya. B, Manoj Kumar, and Ankita Rout. 2024. "Innovative Approaches in Crop Genetic Engineering for Sustainable Agriculture: A Review". Journal of Advances in Biology & Biotechnology 27 (8):615-31. https://doi.org/10.9734/jabb/2024/v27i81177.*

ABSTRACT

Genetic engineering has transformed modern agriculture, offering solutions to enhance crop productivity, resilience, and nutritional quality. This review explores the innovations and challenges in crop genetic engineering, focusing on key techniques such as CRISPR-Cas systems, RNA interference, and transgenic methods. These technologies have facilitated the development of stress-resilient crops capable of withstanding drought, salinity, heat, and cold, thereby supporting agricultural sustainability in the face of climate change. Nutrient use efficiency has been improved through genetic modifications that enhance nitrogen and phosphorus uptake, reducing the reliance on chemical fertilizers and minimizing environmental impacts. Additionally, genetic engineering has advanced pest and disease resistance, decreasing the need for chemical pesticides and contributing to environmental conservation. However, the adoption of genetically modified crops is influenced by various socioeconomic factors, including public perception, regulatory frameworks, and intellectual property rights. Ethical concerns regarding biosafety, labeling, and consumer choice persist, necessitating transparent communication and robust risk assessments. Despite technical challenges such as off-target effects and resistance development, innovations like base and prime editing, as well as synthetic biology, offer promising avenues for more precise and efficient genetic modifications. Future research should prioritize the development of climate-resilient and nutritionally enhanced crops, with an emphasis on biofortification to address global micronutrient deficiencies. Integrating digital technologies such as machine learning and big data analytics can accelerate trait discovery and optimize breeding strategies. Moreover, exploring the synergy between genetic engineering and sustainable agricultural practices can promote resilient farming systems that ensure long-term productivity and environmental health. By addressing technical, ethical, and social considerations, genetic engineering can significantly contribute to global food security and sustainability, providing a foundation for future agricultural advancements in an ever-changing world.

Keywords: Genetic engineering; CRISPR-Cas; biofortification; biotechnology.

1. INTRODUCTION

The advent of crop genetic engineering has revolutionized agriculture, offering unprecedented opportunities to enhance crop productivity, resilience, and nutritional value. This technology involves the manipulation of a plant's genetic material using biotechnology to introduce desirable traits that conventional breeding methods cannot achieve. The importance of crop genetic engineering lies in its potential to address some of the most pressing challenges facing global agriculture, including food security, climate change, and sustainable resource use. Crop genetic engineering has become a critical tool in modern agriculture, providing solutions that contribute significantly to food security and agricultural sustainability. With the world population projected to reach nearly 10 billion by 2050, the demand for food is expected to increase substantially, necessitating innovative approaches to enhance crop yields and nutritional quality. Genetic engineering enables the development of crop varieties with enhanced traits such as increased yield, improved nutritional content, and resistance to biotic and abiotic stresses. For instance, genetically engineered (GE) crops like Bt cotton and Bt maize have shown significant reductions in pesticide use, leading to environmental benefits and improved farmer health [1]. Genetic engineering facilitates the development of crops that can thrive in marginal environments, such as areas with poor soil fertility or high salinity. This is crucial for regions facing climate change impacts, where traditional crops may no longer be viable. Through the introduction of genes that confer drought tolerance, researchers have developed crop varieties capable of maintaining productivity under water-limited conditions, thereby contributing to water conservation in agriculture. Sustainable agriculture aims to meet the needs of the present without compromising the ability of future generations to meet their own needs. Crop genetic engineering plays a vital role in this context by enhancing the sustainability of agricultural systems. One of the significant benefits of GE crops is their potential to reduce the environmental impact of agriculture. For example, herbicide-tolerant crops have led to the adoption of conservation tillage practices, which help to improve soil health and reduce greenhouse gas emissions [2]. The development of pest-resistant crops through genetic engineering reduces the reliance on chemical pesticides, thereby decreasing the negative impacts on biodiversity and non-target organisms. This reduction in pesticide use not only contributes to environmental sustainability but also promotes economic sustainability by lowering production costs for farmers. Biofortified crops, such as golden rice enriched with vitamin A, exemplify the potential of genetic engineering to address malnutrition, particularly in developing countries where micronutrient deficiencies are prevalent [3]. This review aims to explore the innovative approaches in crop genetic engineering that contribute to sustainable agriculture. It will examine the various techniques used in genetic engineering, including CRISPR-Cas9, RNA interference (RNAi), and transgenic methods, highlighting their applications and impact on agricultural sustainability. The review will also address the challenges and controversies associated with the adoption of genetically engineered crops, such as regulatory hurdles, public perception, and ethical considerations. The scope of this review encompasses recent advancements in genetic engineering technologies and their role in developing crops with enhanced traits. It will provide an analysis of the environmental, economic, and social implications of adopting genetically engineered crops, supported by data and case studies from various regions. By evaluating the current state of research and identifying future directions, this review aims to contribute to the ongoing discourse on the role of genetic engineering in achieving sustainable agricultural systems.

2. HISTORICAL DEVELOPMENT OF GENETIC ENGINEERING IN AGRICULTURE

The journey of genetic engineering in agriculture is marked by significant milestones and the continuous evolution of techniques that have reshaped modern farming [4].

2.1 Early Milestones

The foundation of genetic engineering in agriculture can be traced back to the discovery of the DNA double helix structure by James Watson and Francis Crick, which revolutionized the understanding of genetic material. This discovery laid the groundwork for subsequent advancements in genetic manipulation. In the 1970s, the development of recombinant DNA technology marked the beginning of modern genetic engineering. Paul Berg and his colleagues were pioneers in this field, successfully splicing DNA from different organisms to create recombinant molecules. This breakthrough enabled the transfer of specific genes across species, providing the basis for the development of genetically modified organisms (GMOs). The first genetically engineered plant, an antibiotic-resistant tobacco plant, was produced in 1983 using Agrobacterium tumefaciens, a bacterium that naturally transfers DNA to plants. This marked a significant milestone, demonstrating the feasibility of genetic engineering in plants. In the following years, the development of the first genetically modified crop, the Flavr Savr tomato showcased the potential for improving shelf-life and quality through genetic modifications [5].

2.2 Evolution of Techniques

The evolution of techniques in genetic engineering has been characterized by significant advancements that have improved precision, efficiency, and scope. Early methods primarily relied on Agrobacterium-mediated transformation and gene gun technology. Agrobacterium tumefaciens transfers T-DNA into the plant genome, a method that proved highly effective for dicotyledonous plants. The gene gun or biolistic method allowed for direct DNA delivery into plant cells, expanding the range of species that could be genetically engineered, including monocots like maize and rice. In the late 20th and early 21st centuries, the development of more advanced techniques such as RNA interference (RNAi) and zinc-finger nucleases (ZFNs) marked a shift towards more targeted gene modification. RNAi, enables gene silencing by degrading mRNA, providing a powerful tool for regulating gene expression in plants [6]. This technique has been used to develop crops with resistance to viruses and pests, such as the virus-resistant papaya. The advent of CRISPR-Cas9 in 2012 revolutionized genetic engineering, offering unprecedented precision and simplicity. CRISPR-Cas9 uses a guide RNA to direct the Cas9 enzyme to specific DNA sequences, allowing for precise editing. This technology has rapidly become the method of choice for crop genetic engineering, facilitating the development of crops with enhanced traits such as drought tolerance, disease resistance, and improved nutritional content [7]. Gene editing

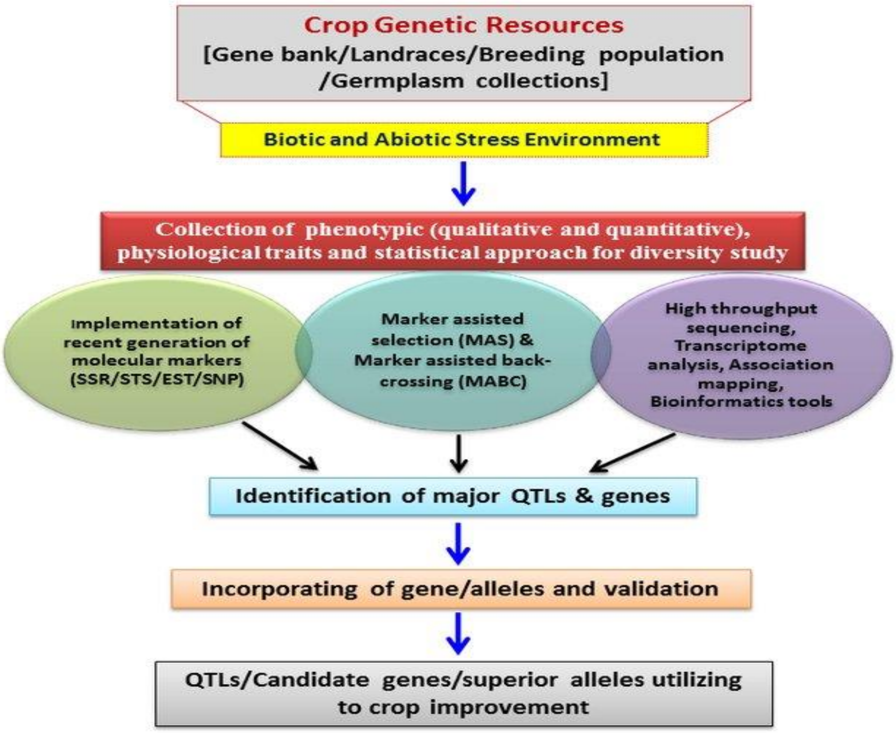

Fig. 1. Evolution of agronomic traits in plants through the utilization of distant alleles present in different gene pools

techniques have continued to evolve, with the development of CRISPR-Cas variants and base editors that allow for even more precise modifications without introducing double-strand break. These advancements have broadened the scope of genetic engineering, enabling the development of crops that address global challenges such as climate change and food security. The historical trajectory of genetic engineering in agriculture reflects the continuous refinement of techniques that have expanded the potential of crop improvement. From the early milestones of recombinant DNA technology to the cutting-edge CRISPR-Cas9 system, each advancement has contributed to the ongoing evolution of sustainable agricultural practices, addressing the growing needs of a changing world.

3. MODERN TECHNIQUES IN CROP GENETIC ENGINEERING

Crop genetic engineering has evolved significantly with the advent of modern biotechnological techniques. These advancements have paved the way for more precise, efficient, and diverse applications in improving crop traits [8]. CRISPR-Cas systems, RNA interference (RNAi), transgenic methods, and gene silencing technologies.

3.1 CRISPR-Cas Systems

CRISPR-Cas (Clustered Regularly Interspaced Short Palindromic Repeats-CRISPR-associated proteins) systems have revolutionized genetic engineering due to their simplicity, precision, and versatility. Discovered in bacteria as an adaptive immune system, CRISPR-Cas9 was adapted for genome editing. The system utilizes a guide RNA (gRNA) to direct the Cas9 nuclease to a specific DNA sequence, where it introduces a double-strand break. This break is then repaired by the cell's natural repair mechanisms, either through non-homologous end joining (NHEJ) or homology-directed repair (HDR), enabling targeted gene modifications [9]. CRISPR-Cas systems have been widely applied in crop improvement. For example, researchers have used CRISPR-Cas9 to develop rice varieties with increased yield and disease resistance by targeting and editing specific genes involved in growth and pathogen response. In maize, CRISPR-Cas9 has been employed to enhance drought tolerance by modifying genes related to stress response pathways. Additionally,

Table 1. Selective genetically modified crops approved for commercial planting worldwide

Commercial Trait	Crops	GM Trait	Developer(s)
Herbicide Tolerance	Alfalfa	Glyphosate tolerance	Monsanto Company & Forage Genetics International
	Canola	Glyphosate tolerance	DuPont (Pioneer Hi-Bred International Inc.), Monsanto Company
		Glufosinate tolerance	Bayer CropScience
	Carnation	Sulfonylurea tolerance	Suntory Limited (Japan)
	Cotton	Sulfonylurea tolerance	DuPont (Pioneer Hi-Bred International Inc.)
		Glufosinate tolerance	Bayer CropScience
		2,4-D herbicide tolerance	Dow AgroSciences LLC
		Oxynil herbicide tolerance	Monsanto Company
		Glyphosate tolerance	Syngenta and Monsanto Company, Bayer CropScience
	Chicory	Glufosinate tolerance	Bejo Zaden BV (Netherlands)
	Flax	Sulfonylurea tolerance	University of Saskatchewan
	Maize	Glufosinate tolerance	Syngenta, DuPont (Pioneer Hi-Bred International Inc.), Bayer CropScience
		Glyphosate tolerance	Monsanto Company
	Rice	Glufosinate tolerance	Bayer CropScience
	Soybean	Glufosinate tolerance	BASF
		Dicamba tolerance	DuPont (Pioneer Hi-Bred International Inc.)
		Glufosinate tolerance	Bayer CropScience
	Wheat	Glyphosate tolerance	Monsanto Company
Insect Resistance	Cotton	Lepidopteran insect resistance	Dow AgroSciences LLC, Syngenta, JK Agri Genetics Ltd (India), Monsanto Company
	Rice	Lepidopteran insect resistance	Huazhong Agricultural University (China), Agricultural Biotech Research Institute (Iran)
	Soybean	Lepidopteran insect resistance	Dow AgroSciences LLC, Monsanto Company
	Tomato	Lepidopteran insect resistance	Monsanto Company
Abiotic Stress Tolerance	Maize	Drought stress tolerance	Monsanto Company
	Soybean	Drought stress tolerance	Verdeca
	Sugarcane	Drought stress tolerance	PT Perkebunan Nusantara XI (Persero)
Altered Growth/Yield	Maize	Enhanced Photosynthesis/Yield	Dow AgroSciences LLC
		Increased Ear Biomass	Monsanto Company
	Eucalyptus	Volumetric Wood Increase	FuturaGene Group

Commercial Trait	Crops	GM Trait	Developer(s)
	Soybean	Enhanced Photosynthesis/Yield	Monsanto Company
Modified Product Quality	Alfalfa	Altered lignin production	Monsanto Company and Forage Genetics International
	Apple	Non-Browning	Okanagan Specialty Fruits Incorporated
	Argentine Canola	Modified oil/fatty acid	Monsanto Company
			Nuseed Pty Ltd
		Phytase Production	BASF
	Cotton	Low Gossypol	Texas A&M AgriLife Research University
	Maize	Modified alpha amylase	Syngenta
		Mannose metabolism	Syngenta
		Phytase production	Origin Agritech (China)
	Rice	Anti-allergy	National Institute of Agrobiological Sciences (Japan)
		Enhanced Provitamin A Content	International Rice Research Institute
	Soybean	Modified oil/fatty acid	DuPont (Pioneer Hi-Bred International Inc.), Monsanto Company
	Tomato	Delayed ripening/senescence	DNA Plant Technology Corporation (USA), Agritope Inc. (USA), Monsanto Company
		Delayed fruit softening	Zeneca Plant Science and Petoseed Company
		Delayed fruit softening (FLAVR SAVR)	Monsanto Company

(Source: GM Approval Database, www.isaaa.org)

CRISPR-Cas systems have facilitated the biofortification of crops, such as increasing the iron content in rice grains by targeting genes involved in iron homeostasis.

3.2 RNA Interference (RNAi)

RNA interference (RNAi) is a gene silencing technique that uses small RNA molecules to inhibit gene expression. RNAi operates by degrading messenger RNA (mRNA) corresponding to specific genes, thus preventing protein synthesis [10]. This method involves introducing double-stranded RNA (dsRNA) or small interfering RNA (siRNA) into the plant, which is processed by the cellular machinery into active siRNA molecules that guide the degradation of target mRNA. RNAi has been instrumental in developing crops with enhanced resistance to pests and diseases. One notable case study is the development of virus-resistant papaya, which employs RNAi to target the Papaya ringspot virus (PRSV) genome, thereby conferring resistance to the disease. Similarly, RNAi has been used to produce potato varieties resistant to the Colorado potato beetle by silencing genes essential for the insect's survival. In addition to pest and disease resistance, RNAi has been applied to improve crop quality traits. For instance, RNAi technology has been used to reduce the expression of allergenic proteins in peanuts, making them safer for consumption by individuals with peanut allergies [11].

3.3 Transgenic Methods

Transgenic methods involve the introduction of foreign genes into a plant's genome to confer new traits (Table 1). These methods typically use Agrobacterium tumefaciens-mediated transformation or biolistic (gene gun) methods. Agrobacterium-mediated transformation exploits the bacterium's natural ability to transfer DNA to plant cells, integrating the foreign gene into the plant genome. The gene gun method, on the other hand, physically delivers DNA-coated particles into plant tissues, facilitating gene integration. Transgenic crops have had a profound impact on agriculture. One of the earliest and most successful examples is Bt cotton, which incorporates genes from the bacterium Bacillus thuringiensis to produce insecticidal proteins. Bt cotton has significantly reduced the need for chemical insecticides, leading to environmental and economic benefits. Another notable transgenic crop is Golden Rice, engineered to produce beta-carotene, a precursor of vitamin A, to address vitamin A deficiency in developing countries [12]. Transgenic methods have also been used to develop herbicide-tolerant crops, such as glyphosate-resistant soybean and maize. These crops allow farmers to use glyphosate for weed control without damaging the crop, enhancing agricultural productivity and reducing soil erosion through no-till farming practices.

3.4 Gene Silencing Technologies

Gene silencing technologies encompass various methods that inhibit gene expression at the transcriptional or post-transcriptional level. In addition to RNAi, other notable technologies include antisense RNA, microRNAs (miRNAs), and transcriptional gene silencing (TGS) using DNA methylation. Antisense RNA technology involves the introduction of RNA sequences complementary to the target mRNA, blocking its translation into protein. This technique has been used to develop crops with improved traits, such as the Flavr Savr tomato, which has delayed ripening due to the silencing of polygalacturonase, an enzyme involved in cell wall degradation [13]. MicroRNAs (miRNAs) are endogenous small RNAs that regulate gene expression by targeting mRNAs for degradation or translational repression. Manipulating miRNA pathways has shown potential in enhancing crop traits. For example, overexpression of miR156 in switchgrass has been demonstrated to increase biomass yield and improve resistance to drought. Transcriptional gene silencing (TGS) involves modifying the epigenetic state of a gene, such as DNA methylation or histone modification, to prevent its transcription. This approach has been explored to confer virus resistance in crops by silencing viral promoters [14]. Gene silencing technologies offer versatile tools for crop improvement, enabling the fine-tuning of gene expression to enhance desirable traits while minimizing off-target effects. These innovations continue to expand the possibilities for sustainable agriculture through precise and targeted genetic modifications.

4. INNOVATIONS FOR SUSTAINABLE AGRICULTURE

The continuous pursuit of sustainable agriculture has led to significant innovations in crop genetic engineering. These innovations are aimed at enhancing crop resilience to environmental stressors, improving nutrient use efficiency, and increasing resistance to pests and diseases.

4.1 Stress-Resilient Crop Development

Drought and salinity are two of the most significant abiotic stress factors affecting crop productivity worldwide. Genetic engineering has facilitated the development of crops with enhanced tolerance to these stresses, contributing to agricultural sustainability in regions prone to harsh environmental conditions. Advances in genetic engineering have enabled the identification and manipulation of genes associated with drought tolerance. For example, the overexpression of the DREB1A (Dehydration-Responsive Element-Binding) transcription factor in transgenic wheat has been shown to improve drought tolerance by enhancing the expression of stress-responsive genes [15]. Similarly, the introduction of the gene OsNAC10 in rice resulted in improved drought resistance, increased root biomass, and enhanced yield under water-limited conditions. These genetic modifications allow plants to maintain growth and productivity despite water scarcity, contributing to water conservation and sustainable agriculture. Salinity stress affects millions of hectares of arable land, reducing crop yields. Genetic engineering has provided tools to enhance salinity tolerance in crops. For instance, the overexpression of the AtNHX1 gene, which encodes a vacuolar Na+/H+ antiporter, in transgenic tomato plants improved their salinity tolerance by facilitating the sequestration of sodium ions into vacuoles, thereby reducing their toxic effects. In another study, the expression of the salt overly sensitive (SOS) pathway genes in rice led to enhanced salt tolerance by improving ionic balance and reducing oxidative stress [16]. These innovations enable crops to thrive in saline soils, expanding the range of cultivable land and contributing to food security.

4.1.1 Heat and cold resistance

Temperature extremes pose a significant threat to crop productivity, with both high and low temperatures adversely affecting plant growth and development.Genetic engineering has enabled the development of crops that can withstand high temperatures, which are becoming increasingly common due to climate change. The overexpression of heat shock proteins (HSPs) in crops such as wheat and maize has been shown to improve thermotolerance by stabilizing proteins and membranes under heat stress conditions. In rice, the overexpression of the HsfA2 transcription factor enhanced heat tolerance by upregulating the expression of heat-responsive genes, leading to increased survival rates and grain yield under heat stress [17]. Low temperatures can impair plant metabolism and growth, particularly in temperate regions. Genetic engineering has facilitated the development of cold-tolerant crops by manipulating genes involved in cold acclimation. For example, the expression of the CBF (C-repeat binding factor) transcription factors in Arabidopsis has been shown to enhance cold tolerance by regulating the expression of cold-responsive genes. Similarly, the introduction of the ANTARCTIC1 gene in rice improved cold tolerance, resulting in better seedling growth and survival under cold stress conditions [18]. These innovations contribute to stable crop yields in regions prone to temperature fluctuations, supporting sustainable agricultural systems.

4.2 Nutrient Use Efficiency

Efficient nutrient use is essential for sustainable agriculture, reducing the environmental impact of fertilizers while maintaining crop productivity. Nitrogen is a critical nutrient for plant growth, but its overuse can lead to environmental issues such as water pollution and greenhouse gas emissions. Genetic engineering has been employed to improve NUE in crops by enhancing nitrogen uptake, assimilation, and utilization. The overexpression of alanine aminotransferase in canola resulted in increased biomass and seed yield under low nitrogen conditions, demonstrating enhanced NUE. In rice, the overexpression of the OsDof1 transcription factor improved nitrogen uptake and assimilation, leading to increased grain yield with reduced nitrogen fertilizer input [19]. Phosphorus is another essential nutrient, but its availability in soil is often limited due to fixation. Genetic engineering approaches have focused on enhancing PUE by modifying root architecture and phosphorus transporters. The expression of the PSTOL1 (phosphorus-starvation tolerance 1) gene in rice improved root growth and phosphorus uptake, resulting in increased yield in phosphorus-deficient soils. Additionally, the overexpression of purple acid phosphatases in Arabidopsis enhanced phosphorus acquisition by increasing organic phosphorus hydrolysis in the rhizosphere. These innovations contribute to reduced fertilizer use, lower production costs, and decreased environmental impact.

4.3 Pest and Disease Resistance

Genetic engineering has significantly advanced pest and disease resistance in crops, reducing the reliance on chemical pesticides and promoting sustainable agriculture.One of the most successful applications of genetic engineering is the development of insect-resistant crops through the introduction of Bacillus thuringiensis (Bt) genes. Bt crops, such as Bt cotton and Bt maize, produce insecticidal proteins that target specific pests, reducing the need for chemical insecticides and benefiting both the environment and farmer health [20]. Studies have shown that Bt crops effectively control major pests such as the cotton bollworm and European corn borer, resulting in increased yields and reduced pesticide use. Genetic engineering has also been used to develop disease-resistant crops by introducing resistance genes or RNA interference strategies. For instance, transgenic papaya resistant to Papaya ringspot virus (PRSV) was developed using a coat protein-mediated resistance approach, significantly reducing the impact of the virus on papaya production. In potatoes, the introduction of the Rpi-vnt1 gene conferred resistance to late blight, a devastating disease caused by Phytophthora infestans, resulting in increased yields and reduced fungicide applications [21]. Fungal pathogens pose a significant threat to crop production. Genetic engineering has enabled the development of crops with enhanced resistance to fungal diseases. The overexpression of antifungal proteins, such as chitinases and glucanases, in transgenic wheat has been shown to confer resistance to Fusarium head blight, reducing yield losses and mycotoxin contamination. Similarly, the expression of defensins, small antimicrobial peptides, in transgenic banana plants conferred resistance to Fusarium wilt, a major fungal disease affecting banana production. These strategies in genetic engineering have not only improved crop resilience but also contributed to environmental sustainability by reducing the need for chemical inputs. The outcomes include increased crop productivity, lower production costs, and enhanced food security, making genetic engineering a crucial tool in the pursuit of sustainable agriculture [22].

5. ENHANCEMENTS IN CROP YIELD AND QUALITY

Modern genetic engineering techniques have significantly contributed to improvements in crop yield and quality. These advancements are crucial for meeting the growing global food demand and addressing nutritional deficiencies.

5.1 Genetic Modifications for Yield Improvement

Yield improvement through genetic engineering involves the modification of genes related to plant growth, stress resistance, and resource utilization. These modifications enhance the overall productivity of crops. One notable example is the development of high-yielding rice varieties through the overexpression of the *OsSPL14* gene, which influences plant architecture and tiller number, resulting in increased grain yield [23]. Similarly, the *ZmWAK* gene in maize, which encodes a wall-associated kinase, has been linked to improved grain yield under drought conditions by enhancing root growth and water uptake. In wheat, the introduction of the *Wheat Yield* gene has shown promise in increasing grain size and yield. This gene regulates the expression of several yield-related traits, leading to significant yield improvements in field trials. Additionally, the manipulation of photosynthesis-related genes in crops such as tobacco has demonstrated increased biomass production, suggesting potential applications in staple crops [24].

5.2 Biofortification

Biofortification aims to enhance the nutritional content of crops through genetic engineering, addressing micronutrient deficiencies in populations dependent on staple crops (Table 2). Genetic engineering has been employed to increase the levels of iron and zinc in staple crops. In rice, the overexpression of the *OsNAS2* gene, which encodes nicotianamine synthase, led to higher iron and zinc concentrations in grains, addressing iron deficiency in rice-dependent populations. Similarly, biofortified wheat with enhanced zinc content has been developed through the introduction of genes involved in zinc transport and accumulation [25]. Golden Rice, enriched with beta-carotene, a precursor of vitamin A, is one of the most prominent examples of biofortification. This genetically engineered rice variety aims to combat vitamin A deficiency, a major public health issue in developing countries. Field trials have shown that Golden Rice can provide a substantial portion of the recommended daily intake of vitamin A.Biofortification of crops with folate (vitamin B9) has been achieved in potatoes through the overexpression of genes involved in folate biosynthesis. These genetically engineered potatoes have shown increased

Table 2. Biofortified varieties of crops

Crop	Variety	Nutrient Biofortified	Developer(s)	Region	Year Released
Rice	IR68144	High Iron	International Rice Research Institute	South Asia	2009
	IRRI 127	High Zinc	International Rice Research Institute	South Asia	2013
Wheat	Zincol-2016	High Zinc	International Maize and Wheat Improvement Center (CIMMYT)	Pakistan	2016
	Biofortified Bread Wheat	High Iron and Zinc	HarvestPlus	Multiple regions	Various
Maize	ProVA 1	High Provitamin A	International Maize and Wheat Improvement Center (CIMMYT)	Sub-Saharan Africa	2012
	QPM (Quality Protein Maize)	High Lysine and Tryptophan	International Maize and Wheat Improvement Center (CIMMYT)	Latin America, Africa	Various
Sweet Potato	Orange-fleshed varieties	High Provitamin A	International Potato Center (CIP)	Sub-Saharan Africa	2005
Cassava	Yellow-fleshed varieties	High Provitamin A	International Center for Tropical Agriculture (CIAT)	Sub-Saharan Africa	2011
Beans	High Iron Beans	High Iron	International Center for Tropical Agriculture (CIAT)	Latin America, Africa	Various
Pearl Millet	Dhanashakti	High Iron and Zinc	International Crops Research Institute for the Semi-Arid Tropics (ICRISAT)	India	2014
Banana	NARITA Hybrid	High Provitamin A	National Agricultural Research Organization (NARO), Uganda	East Africa	2017
Sorghum	Biofortified Sorghum	High Iron and Zinc	HarvestPlus	Sub-Saharan Africa	Various

(Source: HarvestPlus, International Rice Research Institute, International Maize and Wheat Improvement Center, International Potato Center, International Center for Tropical Agriculture, International Crops Research Institute for the Semi-Arid Tropics)

folate content, which is essential for preventing neural tube defects and other health issues [26].

5.3 Improvements in Flavor and Shelf-life

Genetic engineering has also focused on enhancing the flavor and shelf-life of fruits and vegetables, which are crucial for consumer acceptance and reducing food waste. Genetic modifications have targeted the enhancement of flavor compounds in crops. For example, tomatoes engineered with higher levels of volatile compounds, such as monoterpenes, have shown improved flavor profiles, making them more appealing to consumers [27]. Similarly, strawberries have been modified to enhance sweetness and aroma through the manipulation of genes involved in sugar and volatile biosynthesis. The extension of shelf-life in perishable crops reduces post-harvest losses and food waste. The Flavr Savr tomato was one of the first genetically engineered crops aimed at delaying ripening by inhibiting the polygalacturonase enzyme, which is responsible for cell wall degradation. More recent advances include the development of non-browning apples and potatoes through RNA interference (RNAi) technology, which silences genes responsible for browning reactions, thereby extending shelf-life and reducing waste [28].

6. ENVIRONMENT AND ECOLOGY

The introduction of genetically engineered (GE) crops has sparked considerable debate regarding their environmental and ecological impacts [28].

6.1 Biodiversity and Ecosystem Impact

The cultivation of GE crops has potential implications for biodiversity, which is critical for ecosystem functioning and resilience. Concerns often focus on the potential reduction of genetic diversity in agroecosystems due to the widespread adoption of a limited number of GE varieties. However, some studies suggest that GE crops can contribute positively to biodiversity by reducing the need for chemical inputs, thereby supporting more diverse agroecosystems. The introduction of GE crops can lead to genetic homogenization, as farmers may prefer high-yielding GE varieties over traditional landraces [29]. This reduction in genetic diversity can make crops more vulnerable to pests and diseases, potentially leading to ecosystem instability.On the other hand, herbicide-tolerant GE crops have facilitated the adoption of conservation tillage practices, which have positive impacts on biodiversity. Conservation tillage reduces soil disturbance, preserves soil structure, and promotes diverse microbial and invertebrate communities. These practices also enhance water retention and reduce soil erosion, contributing to ecosystem health.Bt crops, which express Bacillus thuringiensis toxins to target specific pests, can lead to reduced pesticide use, thereby preserving non-crop habitats and promoting biodiversity. A meta-analysis showed that Bt crops significantly reduce pesticide applications, contributing to increased populations of beneficial arthropods [30].

6.2 Effects on Non-Target Species

One of the primary ecological concerns associated with GE crops is their potential impact on non-target species, including beneficial insects, birds, and soil organisms.Studies have shown mixed effects of Bt crops on non-target arthropods. Some research indicates that Bt crops have minimal impact on non-target insect populations compared to conventional insecticides. However, concerns remain regarding potential sub-lethal effects and the development of resistance in non-target species [30]. The impact of GE crops on pollinators, such as bees, has been a subject of extensive study. Research has generally shown that Bt crops do not have adverse effects on honeybee populations. Nonetheless, indirect effects, such as changes in weed communities and the availability of forage plants, may influence pollinator diversity and abundance. The introduction of GE crops may also impact soil fauna, including earthworms and other decomposers. Studies have shown that Bt crops have limited effects on soil organism populations, with some research indicating no significant differences in earthworm biomass or activity between Bt and non-Bt crops [31]. However, further long-term studies are needed to fully understand the ecological impacts on soil biota.

6.3 Soil Health and Environmental Services

Soil health is a critical component of sustainable agriculture, and the cultivation of GE crops can have both positive and negative effects on soil ecosystems.The impact of GE crops on soil microbial communities has been widely studied. Some studies suggest that Bt crops can alter soil microbial diversity, particularly the communities associated with the decomposition of crop residues. However, the changes observed are often transient and similar to those induced by conventional agricultural practices.GE crops, particularly those engineered for enhanced nutrient use efficiency, can positively affect nutrient cycling and soil fertility. For instance, crops engineered to express nitrogen use efficiency traits can reduce the need for synthetic fertilizers, thereby minimizing nutrient runoff and improving soil health [32]. Enhanced phosphorus uptake in genetically engineered crops also contributes to more sustainable nutrient management, reducing phosphorus leaching into water bodies. The adoption of conservation tillage practices associated with herbicide-tolerant crops can enhance soil carbon sequestration by promoting the accumulation of organic matter in the soil. This contributes to mitigating climate change by reducing atmospheric carbon dioxide levels and improving soil structure and fertility. GE crops that support conservation practices help reduce soil erosion and improve water retention. Reduced soil disturbance from tillage preserves soil structure and increases the soil’s ability to retain water, which is particularly beneficial in regions prone to drought [33]. The environmental and ecological considerations of GE crops are multifaceted, with both positive and negative implications. While concerns about biodiversity, non-target species, and soil health persist, evidence suggests that the careful management and implementation of GE crops can contribute to sustainable agricultural systems that support biodiversity and enhance ecosystem services.

7. SOCIOECONOMIC IMPACTS

The adoption of genetically modified (GM) crops has significantly influenced global agriculture, presenting various socioeconomic implications [34].

7.1 Adoption of GM Crops

The adoption of GM crops has steadily increased since their introduction in the mid-1990s. GM crops were cultivated on 190.4 million hectares across 29 countries, with the United States, Brazil, Argentina, and Canada being the leading adopters [35]. The rapid adoption of GM crops is attributed to their agronomic benefits, such as increased yield, reduced pesticide use, and enhanced tolerance to biotic and abiotic stresses. Farmers have embraced GM crops primarily due to their ability to simplify pest and weed management, leading to lower production costs and reduced labor. The adoption rates are particularly high for crops such as soybeans, maize, cotton, and canola, which account for the majority of global GM crop acreage [36]. In developing countries, the adoption of GM crops has been driven by the need to enhance food security and improve smallholder farmers' livelihoods. Despite their benefits, the adoption of GM crops faces several barriers, including public resistance, regulatory hurdles, and concerns about environmental and health impacts. In Europe, stringent regulations and public opposition have limited the adoption of GM crops, with only a few countries, such as Spain and Portugal, cultivating Bt maize. Additionally, the lack of infrastructure and resources for smallholder farmers in developing countries can hinder the widespread adoption of GM technology [37].

7.2 Economic Benefits and Barriers

The economic impact of GM crops has been widely studied, with numerous reports highlighting significant benefits for farmers, consumers, and the agricultural industry.GM crops have contributed to increased farm income through higher yields and reduced input costs. A meta-analysis found that, on average, GM crop adoption resulted in a 21% increase in yield and a 39% reduction in pesticide use. This translates to an average increase in farmer profits of 68%. Insect-resistant Bt crops have significantly reduced the need for chemical insecticides, leading to cost savings and environmental benefits [38]. In addition to direct economic benefits, GM crops contribute to broader economic gains by enhancing global food security and reducing the pressure on natural resources. For instance, herbicide-tolerant crops facilitate conservation tillage practices, which improve soil health and reduce erosion, contributing to long-term agricultural sustainability [39]. Despite these benefits, several barriers can limit the economic potential of GM crops. Intellectual property rights and seed costs can pose significant challenges for smallholder farmers, particularly in developing countries. The monopolization of seed markets by a few multinational companies has raised concerns about the affordability and accessibility of GM seeds. Additionally, the emergence of pest resistance and weed tolerance to herbicides can undermine the long-term economic benefits of GM crops [40].

7.3 Regulatory and Policy Issues

Regulatory frameworks and policy issues play a crucial role in the adoption and commercialization of GM crops. These regulations vary significantly across countries, influencing the pace and extent of GM crop adoption. In the United States, the regulation of GM crops involves multiple agencies, including the USDA, EPA, and FDA, each overseeing different aspects of biotechnology products. The regulatory process in the U.S. is considered relatively streamlined, facilitating the rapid commercialization of GM crops. In contrast, the European Union has a more stringent regulatory framework, requiring extensive environmental and health risk assessments before approving GM crops for cultivation or importation [41]. The coexistence of GM and non-GM crops presents policy challenges, particularly regarding labeling, segregation, and market access. Many countries have implemented mandatory labeling of GM foods, aiming to provide consumers with information and choice. However, labeling requirements can increase production and compliance costs, potentially impacting market competitiveness. International trade policies and market access also play a critical role in the adoption of GM crops. Some countries have imposed import restrictions on GM crops, affecting the global trade dynamics of agricultural commodities. For example, China's strict import regulations for GM crops have influenced the export strategies of major soybean-producing countries [42].

8. CHALLENGES AND FUTURE

8.1 Technical Challenges and Innovations

The field of genetic engineering faces several technical challenges that must be addressed to maximize its potential in agriculture. One significant challenge is the occurrence of off-target effects, particularly in CRISPR-Cas9 applications. These unintended genetic modifications can lead to undesirable traits, impacting plant health and safety [43]. Although advances in CRISPR technology have enhanced target specificity, ongoing research is required to further reduce these risks. Resistance development in pests and weeds is another critical issue. For instance, certain insect populations have developed resistance to Bt crops, necessitating increased pesticide use and undermining the environmental benefits of GM crops. Strategies such as gene stacking and the implementation of refuge areas are being explored to delay resistance, but these approaches require continuous innovation and adaptation [44]. Gene delivery and stable integration into plant genomes remain substantial hurdles. Traditional methods, including Agrobacterium-mediated transformation and biolistic techniques, have limitations in terms of species specificity and gene copy number control. To overcome these barriers, researchers are developing novel delivery methods, such as nanoparticle-based systems and electroporation, which show promise in improving efficiency and precision [45]. The regulatory landscape for GM crops is complex and varies significantly across regions, often leading to delays in commercialization and increased costs. Harmonizing regulatory frameworks and streamlining approval processes are essential to facilitate the adoption of new technologies and ensure safety [46]. Recent innovations in genetic engineering offer solutions to some of these challenges. Base editing and prime editing represent significant advancements, allowing precise DNA modifications without causing double-strand breaks. Base editing enables the direct conversion of one nucleotide to another, reducing the potential for off-target effects. Multiplexed CRISPR systems facilitate the simultaneous editing of multiple genes, enabling the stacking of beneficial traits, such as disease resistance and stress tolerance [47]. The integration of synthetic biology into crop genetic engineering is paving the way for novel trait development. This approach involves designing and constructing new biological parts to enhance plant functions, such as nitrogen fixation in non-leguminous crops, offering significant potential for sustainable agriculture [48].

8.2 Ethical and Social Considerations

Ethical and social considerations play a crucial role in the acceptance and adoption of GM crops. Public perception varies widely across regions and is influenced by cultural, social, and political factors. Misinformation and lack of awareness about genetic engineering contribute to public skepticism and resistance. Improving public understanding and ensuring transparency in genetic engineering practices are vital for fostering acceptance [49]. Intellectual property rights and the concentration of patent ownership among a few multinational corporations raise concerns about access to technology, particularly for smallholder farmers in developing countries. This monopolization can limit seed availability and increase costs, exacerbating socioeconomic disparities and hindering the equitable distribution of technological benefits [50]. Biosafety and environmental concerns are significant ethical considerations. Potential ecological impacts of GM crops, such as gene flow to wild relatives and effects on non-target species, remain contentious. While many studies have shown limited adverse impacts, ongoing monitoring and risk assessments are necessary to address public and environmental concerns [51]. The debate over labeling GM foods reflects broader ethical questions about consumer rights and informed choice. While some advocate for labeling as a means of transparency, others argue that it may imply unwarranted risks, influencing consumer perceptions negatively [52].

8.3 Future Research in Genetic Engineering

Future research in genetic engineering should focus on several key areas to enhance its contribution to sustainable agriculture. Advancements in genomics and functional genomics are essential for identifying and characterizing genes involved in important agronomic traits. Understanding gene functions will enable targeted genetic modifications to improve crop resilience and productivity [53]. Developing climate-resilient crops is another critical research area. With climate change posing significant challenges to agriculture, genetic engineering can play a crucial role in enhancing drought, heat, and salinity tolerance in staple crops. Research efforts should prioritize the development of crops capable of withstanding extreme weather conditions [54]. Nutritional enhancement through biofortification should also be a priority to address micronutrient deficiencies in vulnerable populations. Genetic engineering can significantly enhance the nutritional profiles of staple crops, contributing to global food security and health [55]. Integrating digital tools such as machine learning and big data analytics into crop genetic engineering can accelerate trait discovery and optimize breeding programs. These technologies can help predict gene interactions and environmental responses, facilitating precision agriculture and improving crop management strategies [56].

9. CONCLUSION

The advancements in crop genetic engineering have significantly contributed to sustainable agriculture by enhancing crop resilience, yield, and nutritional quality. Despite technical challenges such as off-target effects and resistance development, innovations like CRISPR and synthetic biology continue to drive progress. Addressing ethical and social concerns, including public perception and intellectual property rights, is crucial for broader acceptance. Future research should focus on developing climate-resilient and nutritionally enhanced crops, integrating digital technologies, and promoting sustainable agricultural practices. By balancing technological innovation with ethical considerations, genetic engineering can play a vital role in addressing global food security and environmental sustainability challenges, ultimately contributing to a more resilient agricultural system for future generations.

DISCLAIMER (ARTIFICIAL INTELLIGENCE)

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc) and text-to-image generators have been used during writing or editing of manuscripts.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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Peer-review history:
The peer review history for this paper can be accessed here:
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