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A Global Perspective on Genetically Modified Crops: Benefits, Risks, and Future Directions

Exploring GM Crops: Balancing Benefits, Risks, and Global Future Directions

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A Global Perspective on Genetically Modified Crops: Benefits, Risks, and Future Directions

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Abstract

Through the introduction of advantageous foreign genes or the suppression of endogenous gene expression in crop plants, genetic engineering and plant transformation have been essential to crop improvement. Herbicide tolerance, insect resistance, abiotic stress tolerance, disease resistance, and nutritional enhancement are just a few of the beneficial characteristics that genetically modified crops have. Almost 525 distinct transgenic events in 32 crops have been authorized for cultivation in various regions of the world thus far. It has been demonstrated that the use of transgenic technology raises crop yields, lowers CO_2 emissions, decreases the use of pesticides and insecticides, and lowers food production costs. However, worries about possible human toxicity and allergies, possible environmental hazards like the possibility of gene fow, negative effects on non-target organisms, the development of resistance in weeds and insects, etc., are preventing the widespread adoption of transgenic crops carrying foreign genes. Alternative methods including cisgenesis, intragenesis, and most recently, genome editing, have been used as a result of these worries. Some of these alternative technologies can be used to create crop plants devoid of foreign genes; as a result, it is anticipated that these crops will receive regulatory clearances more quickly and be more favoured by consumers than transgenic crops. We provide a thorough update on the present condition of the genetically modified (GM) crops being grown in this review. We also go over the problems preventing the broad use of transgenic genetically modified crops and offer our thoughts on the new methods and instruments created to allay some of these worries.it is expected that these crops will be more popular with consumers and obtain regulatory clearances faster than transgenic crops because some of these alternative technologies can be used to produce crop plants free of foreign genes. In this review, we give a comprehensive update on the current state of the genetically modified (GM) crops under cultivation. We also go over the challenges impeding the broad deployment of transgenic genetically modified crops and share our thoughts on the new ways and instruments devised to assuage some of these anxieties.

Keywords: GM Crops, Agricultural Biotechnology, Transgenic plants, Food security, Sustainable agriculture.

1. Introduction

Food systems are under strain to fulfil present and future global demands due to growing population pressures and rising expectations for quality of life. The massive population growth in underdeveloped and developing nations has led to widespread poverty, food insecurity, and malnutrition. By modifying already-existing genetic resources, biotechnology and genetic engineering have made it possible to improve plants through scientific research and laboratory techniques. Conventional crops have undergone genetic modification for the past fifteen years for a number of reasons, such as increased nutritional value, longer shelf life, and improved agronomic traits like resistance to herbicides, microbes, insects, and other extreme environmental disturbances[1, 2].Plants are constantly being bioengineered and/or genetically engineered (GE)/genetically modified (GM) to improve the food supply by raising crop yields. GM plants are already commonplace globally and may be found in a variety of processed food products [3]. When genetically modified crops were first made available for purchase in the US in 1996, farmers quickly embraced them. The introduction of genetically modified crops during the 20th century led to significant success in raising agricultural production to meet human demands [4]. Recombinant DNA-produced crops and foods have been on the market for less than ten years, and no long-term consequences have been found as of yet. According to an ISB News story from 2001, these foods are much the same as their traditional counterparts. Thus, throughout the history of agriculture and food biotechnology, genetically modified crops have been the most quickly embraced technology[5]. But There is cause for concern as the use of genetic engineering in food plants has raised serious questions about their environmental stability and safety It is commonly acknowledged that no technology is completely safe and that each technological advancement has a unique set of environmental dangers and benefits. It is important to assess the novel features added to transgenic crops for factors like food security, environmental safety, and ethical considerations. The development, selection, and detection of genetically modified crops, as well as the fate of "transgenes" when they are released into the environment, are covered in this review article. It also emphasizes the advantages of genetically modified crops and the restrictions placed on their use by public and regulatory concerns.

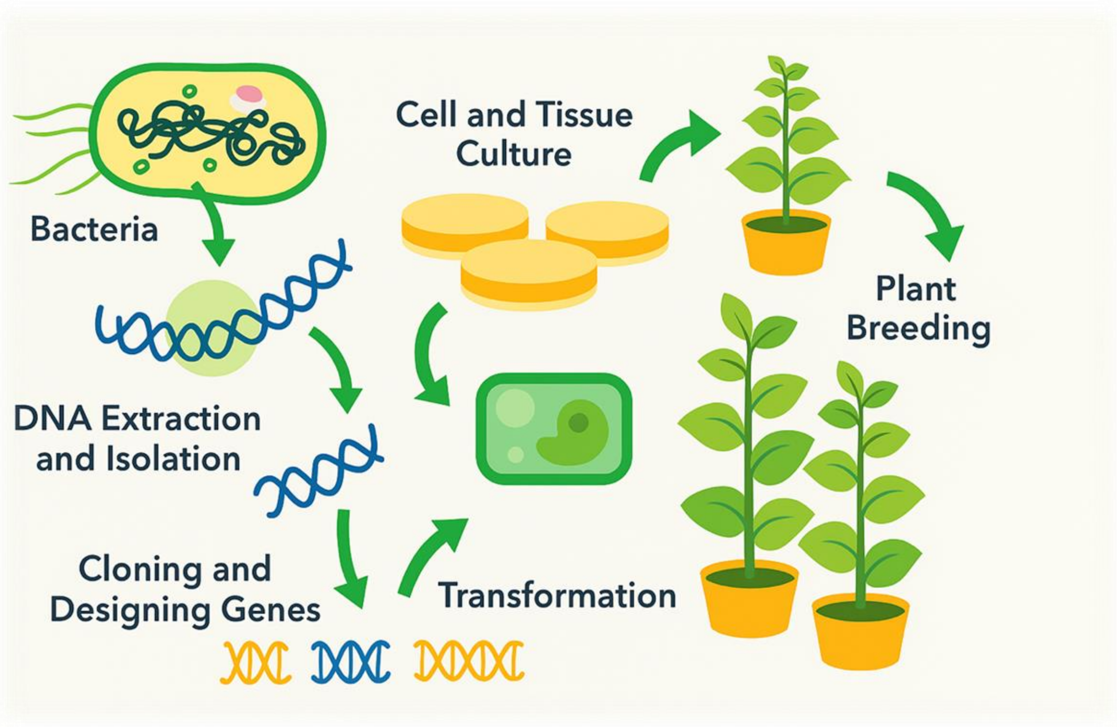

Fig1 :- representation of plant genetic modification, showing the pathway from gene isolation to breeding of genetically modified crops. This process underpins the global discussion on the benefits, risks, and future directions of GM crops.

1.1 History of Genetically Modified Crops

One of the biggest developments in contemporary agricultural biotechnology is the creation of genetically modified (GM) crops. When recombinant DNA technology was discovered in the early 1970s, the history of genetically modified crops began. Genetic engineering was established in 1973 when scientists Stanley Cohen and Herbert Boyer successfully spliced DNA from various organisms[6].A tobacco plant designed to withstand antibiotics was the first genetically modified plant created in 1983[7]. The commercialization of genetically modified crops was made possible by this. The first genetically modified food crop, the Flavr Savr tomato, was approved by the US in 1994. It was designed to have a longer shelf life[8]. It was subsequently discontinued because of production and marketing issues, although it was a landmark in agricultural biotechnology. Herbicide-tolerant soybeans and insect-resistant corn were introduced in 1996, marking the start of the widespread commercialization of genetically modified crops. The genes from Bacillus thuringiensis (Bt), a naturally occurring bacterium that generates proteins poisonous to particular insect pests, were mainly used to create these crops[9]. Global usage of GM crops has increased over time. Over 190 million hectares of genetically modified crops were grown in 29 countries as of 2022, with the United States, Brazil, Argentina, Canada, and India being the main adopters[10]. Nowadays, it's normal practice to engineer traits like drought, insect, viral, and herbicide resistance into staple crop including canola, maize, soybean, and cotton. GM crops have been at the heart of continuous discussions about biosafety, environmental impact, and food security despite their broad use. There are notable regional differences in regulatory frameworks and public opinion, particularly across North America, the European Union, and portions of Asia and Africa [11].

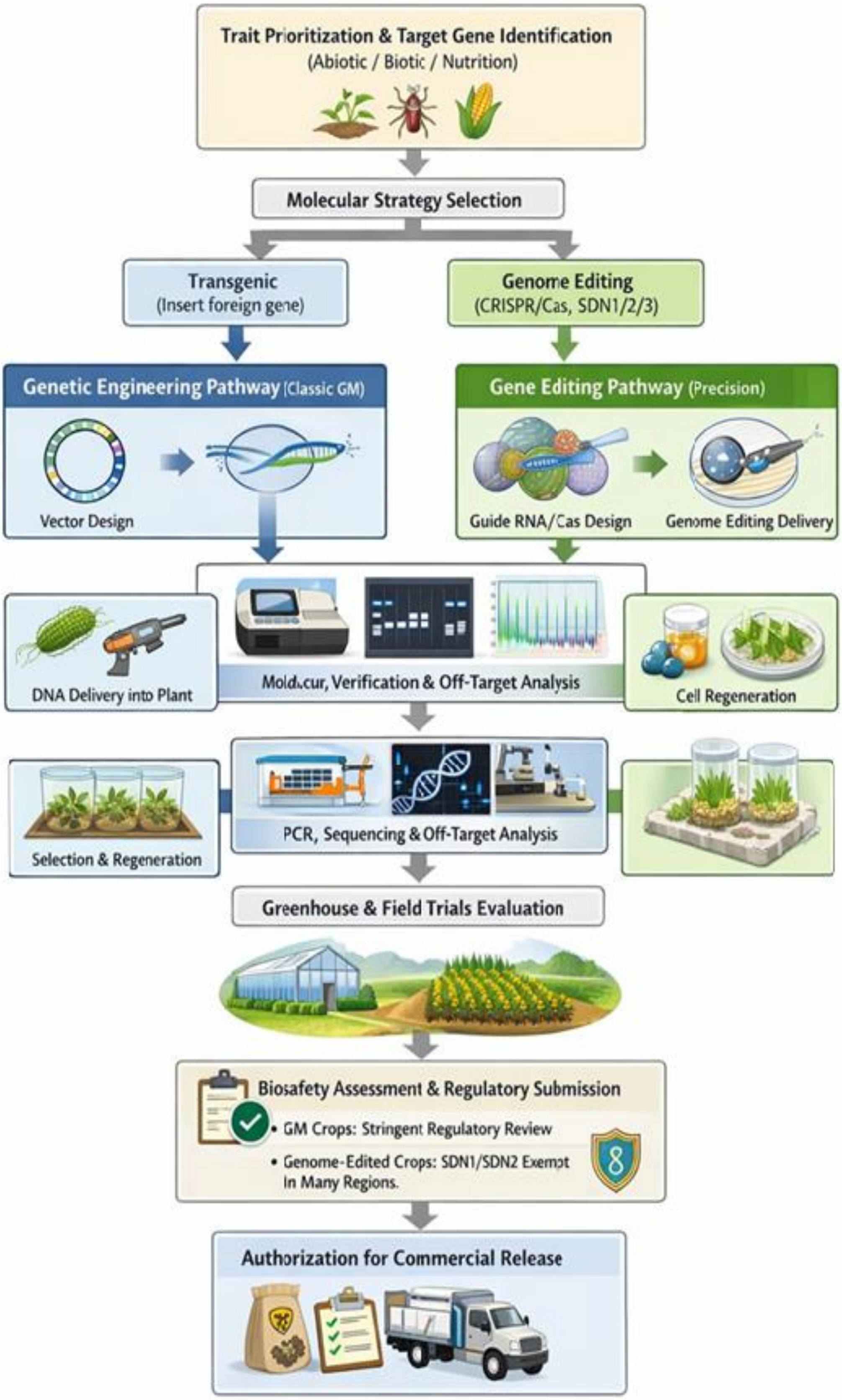

Figure 2:- Workflow of genetically modified and genome-edited crop development from trait identification to commercial

1.2 Application

1.2.1 Pest and Disease Resistance

Increasing crop resistance to plant diseases and insect pests is one of the most well-known uses of genetic manipulation. Plants can produce toxins that are deadly to certain pests like the European corn borer (Ostrinia nubilalis) and cotton bollworm (Helicoverpa armigera) by introducing genes encoding insecticidal proteins from the bacterium Bacillus thuringiensis (Bt) into crops like maize, cotton, and brinjal [12]. By drastically reducing the need for chemical pesticides, this method lowers production costs, minimizes environmental impact, and enhances food product safety. For instance, Bt cotton has been widely used in nations like China and India, which has resulted in higher yields and significant decreases in the usage of pesticides[13]. Additionally, GM crops have been modified to be resistant to fungi and viruses. One effective example is Hawaii's papaya resistant to papaya ringspot virus (PRSV), which prevented the local papaya sector from being destroyed in the 1990s[14].

1.2.2 Herbicide Tolerance

The creation of crops that can withstand particular herbicides, especially glyphosate, is another important use. Crops that are resistant to glyphosate, like canola, maize, and soybean, enable farmers to apply the herbicide directly to fields to manage weeds without causing harm to the crop. This makes controlling weeds easier, uses less herbicides, and encourages the use of conservation tillage techniques, which preserve soil and retain moisture[15].However, glyphosate-resistant weed populations have emerged as a result of long-term reliance on herbicide-tolerant crops, raising questions regarding sustainable management practices and the necessity of integrated weed control tactics [16].

1.2.3. Nutritional Enhancement (Biofortification)

Biofortification is a technique that uses genetic manipulation to increase the nutritional value of crops. In low-income nations, this is especially helpful in correcting micronutrient shortages. Golden rice, which was genetically modified to create beta-carotene, a precursor of vitamin A, in the rice endosperm, is among the most well-known instances. In many regions of Asia and Africa, vitamin A insufficiency is a serious public health issue. Golden rice shows promise as a long-term solution[17]. Additional initiatives include cassava with higher protein content and lower levels of cyanogenic glycosides, as well as genetically modified bananas enhanced with iron and pro-vitamin A [18]. In environments with limited resources, these biofortified crops may be essential in lowering malnutrition and enhancing public health outcomes.

1.2.4. Abiotic Stress Tolerance

Extreme temperatures, salt, and drought are examples of abiotic stresses that significantly reduce agricultural productivity, particularly in light of the growing threat posed by climate change. Crops with increased resistance to these stressors have been created through genetic engineering. For instance, the cold shock protein B gene from Bacillus subtilis has been incorporated into drought-tolerant maize (MON 87460), which aids in preserving plant function in water-limited environments[19]. In field tests carried out in drought-prone regions of Latin America and Sub-Saharan Africa, these crops have shown yield gains[20].To provide wider stress resistance, alternative strategies involve altering Osmo protectant pathways or regulating genes such as DREB (dehydration-responsive element-binding) transcription factors[21].

1.2.5. Improved Post-Harvest Traits and Shelf Life

Through genetic alterations targeted at enhancing shelf life and storage properties, post-harvest losses from spoiling and perishability can be reduced. The first genetically modified food crop to be licensed for commercial use was the Flavr Savr tomato, which was designed to inhibit the enzyme polygalacturonase, which softens fruit. Longer shelf life and postponed ripening were the outcomes of this alteration [8].More recently, RNA interference (RNAi) technology has produced genetically modified potatoes (GM) with lower levels of acrylamide-forming sugars and bruising [22].These upgrades can increase product quality, decrease food waste, and boost marketability.

2. Concerns and Controversies Surrounding Genetically Modified Crops

2.1 Environmental Impacts

The possible ecological effects of GM crops on biodiversity and non-target creatures are a major worry. Gene flow, or the accidental spread of transgenes from GM crops to non-GM or wild cousins by pollen dispersal, is one hotly contested topic. Unintended ecological implications or the formation of "superweeds" could result from this [23].

Concerns have also been raised on how Bt crops may affect helpful pollinators and butterflies, among other non-target insects. Even though extensive research has demonstrated that there is little danger to non-target species in field settings[24], scientists are still looking into the potential for long-term ecosystem change. The development of insect resistance is another environmental concern. Long-term exposure to Bt toxins has reduced the effectiveness of GM crops by creating resistant populations of pests like Helicoverpa zea (corn earworm)[25]. Crop rotation and refuge planting are two integrated pest resistance management techniques that are now required as a result of this.

2.2 Human Health and Food Safety

While the consensus among major scientific organizations is that currently approved GM foods are safe for consumption, some critics raise concerns about the potential for allergenicity, toxicity, and long-term health effects. One controversial case involved a GM soybean engineered with a Brazil nut protein that was later withdrawn due to concerns about allergenic reactions [26].Another ongoing debate concerns the adequacy of regulatory testing, particularly with respect to chronic exposure and the presence of unintended effects due to gene insertion. Although no conclusive evidence of harm has emerged, critics advocate for more rigorous, independent long-term studies to ensure consumer safety [27].

2.3 Socioeconomic Concerns

The commercialization of genetically modified crops presents important socioeconomic challenges, especially with relation to corporate seed control and biotech companies intellectual property rights. According to critics, seed patents and license contracts diminish farmers' autonomy and threaten traditional farming methods, particularly in developing nations[28]. Smallholder farmers' reliance on multinational companies for seeds and pesticides is another issue that raises concerns because it may exacerbate social injustices and economic vulnerabilities[29]. Furthermore, less variety and higher pricing for seeds have resulted from the consolidation of seed markets[30].

2.4 Ethical and Cultural Issues

Concerns about altering nature, the "unnaturalness" of genetic modification, and the freedom to make an educated consumer choice are some of the ethical conundrums raised by GM crops. Religious or cultural convictions are frequently the basis of ethical objections; some groups oppose genetically modified organisms (GMOs) for moral reasons, independent of scientific safety evaluations[31].GM food labeling is still a controversial topic, especially in nations like the US where it is frequently optional. While opponents contend that required labeling could mislead consumers into believing GM foods are harmful, supporters contend that customers have a right to know and make their own decisions [32].

3. Global Adoption and Regulation of Genetically Modified Crops

3.1 Global Adoption Trends

Global acceptance of genetically modified crops has been gradually increasing since the first GM crops were commercialized in 1996. In 2018, 191.7 million hectares of GM crops were farmed worldwide, with the United States, Brazil, Argentina, Canada, and India being the top producers, according to the International Service for the Acquisition of Agri-biotech Applications. Herbicide tolerance and insect resistance are the most prevalent features of the most widely grown genetically modified crops, which include soybean, maize, cotton, and canola. With almost 39% of the world's GM crop production, the United States leads the world in adoption, followed by Brazil (27%), and Argentina (12%) [33].More than half of the world's biotech crop acreage is currently in developing nations, underscoring the growing significance of GM technology in tackling issues related to food security in the Global South. Bt cotton and Bt brinjal have demonstrated remarkable success in raising yields and lowering the use of pesticides in nations like Bangladesh and India[34].

3.1.1 Regional Differences

There is significant regional variation in the uptake of GM crops. Strong agricultural biotechnology sectors in North and South America have embraced and supported GM technology. Simplified regulatory frameworks in nations like the United States, Brazil, and Argentina enable the quick licensing and commercialization of genetically modified crops.

The European Union (EU), on the other hand, continues to take a very cautious approach. Only one GM crop (Bt maize MON810) has been licensed for commercial cultivation in the EU, despite the fact that imports of GM crops for food and feed are allowed under stringent labelling regulations. Strong environmental lobbying and public opposition have had a significant impact on EU policy[35]. Adoption trends in Africa have been impacted by political intent and regulatory capability. Some nations, like Zambia and Algeria, have banned genetically modified crops, while others, including South Africa, Nigeria, and Kenya, have either permitted their use for testing or adopted them. The African Biosafety Network of Expertise (ABNE), which promotes biosafety capacity building throughout the continent, has been adopted, marking regulatory progress [36].

3.2 Regulatory Frameworks

GM crop safety for the environment and human health is evaluated by regulatory frameworks. The structure, level of rigor, and guiding concepts of these systems vary.

3.2.1 **Science-Based vs. Precautionary Regulation**

- **United States**: The United States relies on current regulations that are enforced by the FDA, EPA, and USDA and takes a product-based, science-driven approach. This paradigm places more emphasis on the final product's attributes than the manufacturing process [37].
- **European Union**: Under Regulation (EC) No. 1829/2003, the EU takes a process-based, preventative approach that calls for thorough risk assessments, traceability, and labelling. Despite being centralized, the licensing process permits member states to impose national restrictions on the growing of genetically modified crops [38].

3.2.2 Emerging Economies

- Nations like as China, Brazil, and India have developed biosafety frameworks that incorporate aspects of socioeconomic considerations and scientific risk assessment. The Genetic Engineering Appraisal Committee (GEAC) of India, for instance, regulates the environmental discharge of genetically modified organisms (GMOs); yet, public and political opposition has postponed the commercialization of several crops, such as genetically modified mustard [39].

3.2.3 International Agreements

- The transboundary movement of living modified organisms (LMOs) is governed at the international level by the Cartagena Protocol on Biosafety, which is a component of the Convention on Biological Diversity. Although the United States is not a party to the Protocol, it requires informed consent prior to import and supports biosafety through the precautionary principle [40].

4. Future Prospects of Genetically Modified (GM) Crops

4.1 Climate Resilience and Stress Tolerance

Future genetically modified crops are being created to resist abiotic challenges like salt, drought, and extremely high or low temperature precise alterations made possible by CRISPR/Cas9 and other gene-editing techniques can improve crop resilience without compromising production. As climatic variability poses a growing threat to global agriculture, these characteristics will become increasingly important [41].

4.2 Nutritional Enhancement

Malnutrition may be prevented by biofortification using GM technology. Future crops could be designed to have higher levels of iron, zinc, and critical amino acids, as is the case with Golden Rice, which is enriched with provitamin A [17].

4.3 Sustainable Pest and Disease Management

In order to lessen the need for chemical pesticides, new generations of genetically modified crops are being developed to fight several pests and diseases at once. For example, numerous nations have already seen a large decrease in the use of insecticides due to Bt crops [42].

4.4 Improved Yield and Resource Efficiency

In line with sustainable agriculture objectives, genetic modification that improves photosynthetic and nutrient usage efficiency may boost yields while requiring less input [43].

4.5 **Stacked Traits and Multi-Gene Engineering**

Advanced transformation and synthetic biology techniques will likely enable stacking traits, which are combinations of productivity, tolerance, and resistance traits, in future crops [44]. This will result in crops that are more appropriate for a variety of agro-ecological zones.

4.6 **Regulatory and Public Acceptance Trends**

Regulatory frameworks are changing to adapt to the growing acceptance of gene-editing technologies like CRISPR. The adoption of more lenient regulations by nations like the United States, Brazil, and Japan may hasten the creation and marketing of next-generation genetically modified crops [45].

Table 1: Historical Evolution of Genetically Modified (GM) Crops

Year	Event / Milestone	Description	Reference
1973	Recombinant technology	Development of recombinant DNA technology enabling gene transfer	[6]
1983	First GM plant	Development of antibiotic-resistant tobacco plant	[46]
1992	GMO regulation	FDA establishes policy for GM food safety	[47]
1994	First GM food crop	Flavr Savr tomato approved for commercial use	[8]
1996	Commercial GM crops	Bt cotton and herbicide-tolerant soybean adopted	[9]
2000	Golden Rice	Vitamin A enriched rice developed	[48]
2012	CRISPR-Cas9	Introduction of genome editing technology	[49]
2020–Present	Genome-edited crops	Development of climate-resilient crops	[41]

5. Conclusion

One of the biggest developments in contemporary agricultural biotechnology is genetically modified (GM) crops, which provide a number of advantages such as increased yield, better nutritional value, resistance to pests and diseases, and increased resilience to environmental stressors. GM technology has been crucial in addressing food security, especially in poor nations, as the world's food demands continue to rise in the face of issues like starvation, climate change, and shrinking arable land. But even with their broad use and the generally positive safety evaluations from scientific organizations, genetically modified crops continue to be the focus of intense discussion and scrutiny. Environmental issues that continue to influence public opinion and policy include gene flow, the emergence of pest and weed resistance, and socioeconomic and moral dilemmas related to corporate dominance and consumer rights. The difficulty of global GM crop regulation is highlighted by the disparate legal systems and public perceptions in various geographical areas. In the future, the incorporation of novel technologies such as CRISPR and multi-trait gene stacking holds the potential to further transform crop development. Future developments could greatly support sustainable agriculture in addition to increasing productivity and nutritional value. However, responsible innovation—driven by thorough research, open regulation, and inclusive discourse—remains crucial to guaranteeing that the advantages of genetically modified crops are optimized while lowering any possible hazards.

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