IJCRT.ORG ISSN : 2320-2882

INTERNATIONAL JOURNAL OF CREATIVE RESEARCH THOUGHTS (IJCRT)

An International Open Access, Peer-reviewed, Refereed Journal

Advancements And Challenges Of Genetically Modified Crops In India: A Critical Overview

Gurinder Kaur Walia[1], Diksha Chopra[2*] and Baneet Sidhu[3]

[1]Professor, Department of Zoology and Environmental Sciences, Punjabi University Patiala, Punjab, India

[2]Research Scholar, Department of Zoology and Environmental Sciences, Punjabi University Patiala, Punjab, India

[3]M.Sc. Student, Department of Zoology and Environmental Sciences, Punjabi University Patiala, Punjab, India

ABSTRACT

This critical overview examines the advancements and challenges associated with genetically modified (GM) crops in India, with a focus on their role in addressing food security and agricultural sustainability. Genetic engineering, specifically through the development of GM crops, has emerged as a pivotal solution to meet the increasing food demands of a projected global population of 9.8 billion by 2050. This paper discusses the introduction of transgenic technologies, such as CRISPR-Cas9, which have revolutionized agricultural practices by introducing traits like increased yield, nutritional enhancement, disease resistance, and environmental adaptability into crops. However, the acceptance and regulatory oversight of GM crops continue to pose significant challenges, reflecting concerns over safety, ethics, and environmental impacts. Key historical milestones of GM crops, from the first GM tobacco plants to recent developments like drought-tolerant wheat, illustrate the rapid advancements and the increasing complexity of this field. Furthermore, we address the controversies surrounding GM crops, including health implications and environmental impact, balanced against their potential to substantially improve agricultural productivity and sustainability. The paper emphasizes the need for informed discourse and robust regulatory frameworks to harness the benefits of GM crops while mitigating associated risks, particularly in the context of India's agricultural landscape.

KEYWORDS: GM crops, History, Genetic engineering, Bt crops.

I - INTRODUCTION

The dawn of the 21st century has ushered in an era of unprecedented challenges and opportunities in the field of agriculture, chief among them the imperative to substantially increase food production to feed a global population projected to reach 9.8 billion by the year 2050. This demographic expansion, coupled with the escalating demand for diverse and nutritionally rich diets, necessitates the exploration and adoption of innovative agricultural technologies. Genetic engineering emerges as a pivotal solution in this context, offering the potential to revolutionize food production through the development of genetically modified (GM) crops that promise not only higher yields but also enhanced nutritional profiles, disease resistance, and adaptability to adverse environmental conditions (Nyika et al., 2022).

Transgenic technologies, which allow for the insertion of foreign DNA into plant genomes, have paved the way for the creation of crops with precisely engineered traits, heralding a new era of agricultural productivity and efficiency. This scientific breakthrough holds the promise of transforming not just agricultural practices but also public health paradigms, particularly in developing countries, by enabling the delivery of vaccines and pharmaceuticals through GM crops, thereby circumventing the logistical and financial challenges associated with traditional medical distribution methods (Delaney, 2015; The Guardian, 2016).

Moreover, the advent of genetic engineering in agriculture extends beyond the realm of food security and healthcare, venturing into the domains of environmental sustainability and energy production (Aldemita et al., 2015). The development of GM crops capable of thriving in harsh environmental conditions, or those engineered to produce biofuels, represents a forward-thinking approach to addressing the multifaceted challenges of climate change, energy scarcity, and ecological conservation Techniques like CRISPR-Cas9 have advanced modern genetic engineering by providing increased accuracy and versatility in modifying the genomes of organisms (Gupta et al., 2021). The transition from conventional breeding methods to genetic modification techniques has not been without controversy, particularly with regard to the acceptance and regulatory oversight of GM crops. The distinctions between transgenic, cisgenic, and intragenic modifications highlight the complexity of this scientific frontier, reflecting the nuanced considerations of safety, ethics, and environmental impact that accompany the genetic engineering debate (Schouten et al., 2006; Southgate et al., 1995).

As we stand on the brink of potentially transformative advancements in agricultural science, it is imperative to engage in a comprehensive and informed discourse on the role of genetic engineering in shaping the future of food production, healthcare, and environmental stewardship. This paper aims to provide a critical overview of the developments, challenges, and prospects associated with genetically modified crops, underpinning the discussion with relevant scientific evidence and policy analysis to contribute to a balanced and forward-looking dialogue on this pivotal issue.

II

HISTORY, DISCOVERY AND APPLICATION OF Bt GENES

10,000 years ago, humans began domestication using selective breeding. Farmers and scientists began cross-breeding plants in the 1700s. In order to breed plants with desirable features, researchers develop more accurate and manageable genetic engineering techniques in the 1980s. In 1982, a tobacco plant that was resistant to antibiotics was created as the first genetically modified crop plant (Table:1).

Table:1 History of GM crops

Year	Event	Major Attributes
1982	First GM crop produced: an antibiotic-resistant tobacco plant.	Antibiotic resistance
1986	First field trials in France and the USA with herbicide-resistant tobacco plants.	Herbicide resistance
1987	First company to engineer insect-resistant tobacco plants by incorporating genes from Bacillus thuringiensis (Bt).	Insect resistance
1994	First genetically modified crop approved for sale in the US: FlavrSavr tomato.	Delayed ripening
1994	EU approved tobacco engineered to be resistant to the herbicide bromoxynil, marking the first commercial GM crop in Europe.	Herbicide resistance
1995	Approval of multiple GM crops: Bt maize, bromoxynil-resistant cotton, Bt cotton, glyphosate-resistant soybeans, virus-resistant squash, and additional delayed ripening tomatoes.	Insect resistance, herbicide resistance, virus resistance, delayed ripening
2000	Development of Vitamin A enriched golden rice.	Nutrient enrichment (Vitamin A)
2013	World Food Prize awarded for work on genetic engineering of crops.	Recognition in genetic engineering
2002	Official approval of Bt cotton (Bollgard-I) for commercial cultivation in India, marking the first genetically modified crop in the country.	Insect resistance

2018	Approval of the first genetically modified salmon for human consumption in the USA.	Enhanced growth
2021	Introduction of drought-tolerant genetically modified wheat in Australia, marking a significant step towards climate-resilient crops.	Drought tolerance

Bacillus thuringiensis, commonly known as Bt, is a bacterium initially identified by the Japanese biologist Shigetane Ishiwatari and later characterized by Ernst Berliner in 1911 after he isolated it from a Mediterranean flour moth in Thuringia, Germany. The discovery of crystal proteins within Bt, which occurred in 1915 (Sanahuja et al., 2011), laid the groundwork for understanding its insecticidal properties, although the mechanism of action was not elucidated until much later. These proteins, once ingested by insect larvae, become activated in the larval midguts, proving fatal. The bacterium produces a variety of Cry proteins, each targeting different insect orders, leading to its incorporation into genetically modified crops such as cotton (with genes Cry1Ac, Cry2Ab2, Cry1Fa2), maize (Cry1Ab, Cry1Ac, Cry1Fa2, Cry3Bb1, Cry9C), and potato (Cry3Aa) to combat pests (Kumar and Kumar, 2004); Hellmich and Hellmich, 2012).

Bacillus thuringiensis serves as a natural and effective biopesticide. It harbors a diverse array of insecticidal proteins, including δ-endotoxins, which have been notably successful in protecting crops from various pests. Bt's application has been widespread across stored grains, ornamental plants, forest trees, and food crops for an extended period, evidencing its versatility and efficacy (Meadows, 1993). Unlike chemical pesticides, Bt's specificity and high toxicity towards insects, coupled with its safety for humans, animals, and non-target species, make it an ideal component of Integrated Pest Management (IPM) strategies (Nester et al., 2002). However, the reliance on Bt-based biopesticides is not without challenges. The necessity for repeated applications and the limited effectiveness against pests that feed internally on plants highlight the limitations of traditional Bt formulations (McGaughey and Whalon, 1992). The genetic engineering of crops to express Bt genes offers a solution to these limitations, allowing for continuous protection against targeted pests without the need for frequent reapplication (Krattiger, 1997).

By integrating Bt genes directly into plant genomes, researchers have unlocked a method to safeguard crops against pests more efficiently, effectively overcoming the constraints faced by conventional Bt biopesticide applications. This innovative approach marks a significant advancement in agricultural biotechnology, offering a sustainable alternative to chemical pesticides and enhancing crop resilience against insect attacks.

GM BRINJAL

Bt Brinjal, developed by Mahyco (Maharashtra Hybrid Seeds Company) in collaboration with American agri-biotech giant Monsanto, contains a gene from the soil bacterium Bacillus thuringiensis (Bt) that imparts resistance to the fruit and shoot borer pest. Bt Brinjal, an eggplant modified to produce a toxin lethal to the fruit and shoot borer, has been banned from commercial cultivation since 2010, though it is permitted for research purposes. It has not been approved for commercial cultivation in any other country (Kiranmai et al., 2021). The Genetic Engineering Appraisal Committee (GEAC) approved the commercial release of Bt Brinjal in 2009. However, this decision was met with widespread opposition from various stakeholders, including farmers, environmentalists, and scientists, who raised concerns about biosafety and the impact on biodiversity. In 2010, the then Environment Minister, Jairam Ramesh, imposed an indefinite moratorium on its release, citing the need for further independent studies and public consultations (Shiva, 2010).

GM COTTON

Bt cotton is a genetically modified variety of cotton that contains a gene from the soil bacterium Bacillus thuringiensis (Bt). Bt Cotton, which has been engineered to generate a toxin effective against the cotton bollworm, received commercial authorization in 2002. It is broadly grown in countries including the USA, Brazil, Argentina, and Australia (Fabrick et al., 2023). Bt cotton was first introduced in India in 2002 by Monsanto-Mahyco. Since its introduction, Bt cotton has seen widespread adoption among Indian farmers due to its effectiveness in controlling pests and increasing yields. By 2019, Bt cotton accounted for more than 90% of the cotton cultivated in India (Qaim and Zilberman, 2003; Kranthi and Stone, 2020). Bt cotton remains the only GM crop approved for commercial cultivation in India. While it has significantly contributed to increased cotton production, it has also faced several challenges and controversies. These include issues related to pest resistance, secondary pest outbreaks, high seed costs, and concerns over environmental and health impacts (Gruere and Sengupta, 2011).

GM MUSTARD (DHARA MUSTARD HYBRID 11 - DMH-11)

Developed by Delhi University's Centre for Genetic Manipulation of Crop Plants, DMH-11 is a transgenic mustard hybrid containing genes from Bacillus amyloliquefaciens that enable herbicide tolerance and hybrid vigor. The GEAC recommended the commercial release of DMH-11 in 2017. However, the approval has been stalled due to ongoing debates and legal challenges. Environmentalists and farmers' groups have raised concerns about biosafety, potential impact on honeybees, and the dominance of herbicide-tolerant crops. In 2022, the GEAC recommended environmental release trials for GM mustard hybrids, indicating a step towards eventual commercial approval, but widespread cultivation is yet to commence (Pradhan and Singh, 2021).

GM RUBBER

The GM rubber developed by the Rubber Research Institute of India (RRII) is designed to withstand climate change-related stress, such as low temperatures. The gene MnSOD (Manganese-containing superoxide dismutase) from a wild rubber plant species has been inserted to enhance tolerance to abiotic stress. In 2021, India's first GM rubber plant was planted in Assam under controlled conditions. This marks a significant step forward for GM crop research in India, particularly for non-food crops (Thomas and Mathew, 2022).

GM RICE

Research on GM rice in India has focused on developing varieties with traits such as insect resistance (Bt rice), herbicide tolerance, and improved nutritional content (Golden Rice, which contains beta-carotene, a precursor of vitamin A) (Prakash and Jayaraman, 2010). As of now, GM rice has not been approved for commercial cultivation in India. Field trials have been conducted for various GM rice varieties, but they remain under regulatory review. Concerns about potential cross-contamination with traditional rice varieties and the impact on export markets have contributed to the cautious approach (Natarajan and Sinha, 2022).

III
GENE TRANSFER TECHNOLOGIES IN PLANTS

Several techniques exist for the genetic manipulation of plant cells, including exploiting the natural gene transfer system of Agrobacterium, chemically treating isolated protoplasts with polyethylene glycol, and physical techniques like microinjection, silicon carbide fiber-mediated transformation, and electroporation. Microprojectile bombardment has gained attention as a reliable procedure for producing transgenic plants (Rani and Usha, 2013).

- **GENE TRANSFER BY Agrobacterium tumefaciens**
  Agrobacterium tumefaciens is widely used to introduce genes into plant cells, particularly dicotyledonous plants. The bacterium carries a tumor-inducing plasmid (Ti plasmid) responsible for crown gall disease, used to transfer genes to host plant cells (Hooykaas et al., 1985).
- **Microprojectile Bombardment**
  Sanford et al., 1987 introduced the technique of transferring DNA-coated particles into cells. This method involves propelling DNA-coated metal particles into target cells using compressed gas or gunpowder, and it has become a common method for creating transgenic plants (Klein et al., 1992).
- **Electroporation of Protoplasts**
  Protoplasts mixed with plasmid DNA are exposed to an electric field, leading to the uptake of DNA. This method has been successfully used to transform maize and rice protoplasts (Fisk and Dandekar, 2005).
- **Polyethylene Glycol (PEG)**
  PEG stimulates endocytosis in protoplasts, facilitating DNA uptake. After exposure to DNA and PEG, protoplasts are cultured to form cell colonies (Jogdand, 2006).
- **Microinjection**
  DNA is introduced into the cytoplasm or nucleus using a glass micropipette. This technique is limited in plant cells due to the thick cell walls (Crossway et al., 1986).
- **Liposome-Mediated Gene Transfer**
  Liposomes encapsulate DNA fragments and fuse with cell membranes to deliver DNA into the cell. This method has been used in tobacco and wheat (Dekeyser et al., 1990; Zhu et al., 1993).

- **Pollen Tube Pathway**

  DNA is applied to the cut styles after pollination, allowing it to reach the ovule via the pollen tube. This method has been used in rice, wheat, soybean, petunia, and watermelon (Song et al., 2007).

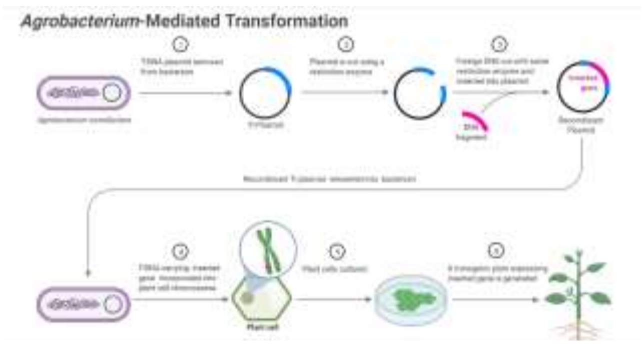

Fig. 1: Gene transfer by *Agrobacterium tumefaciens.*

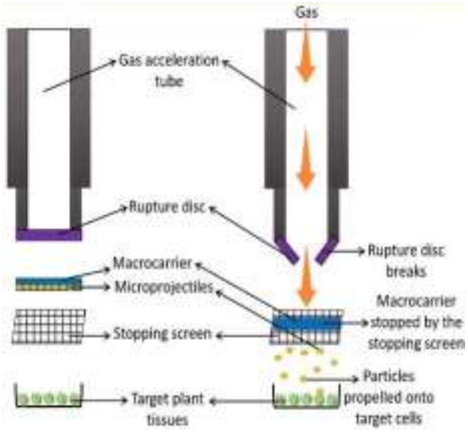

Fig. 2: Microprojectile bombardment.

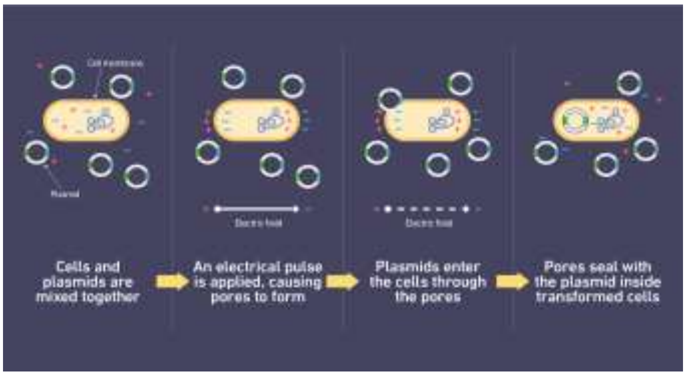

Fig. 3: Electroporation of protoplast.

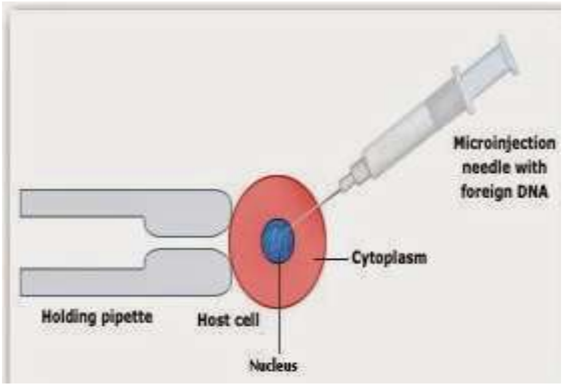

Fig. 4: Gene transfer through microinjection

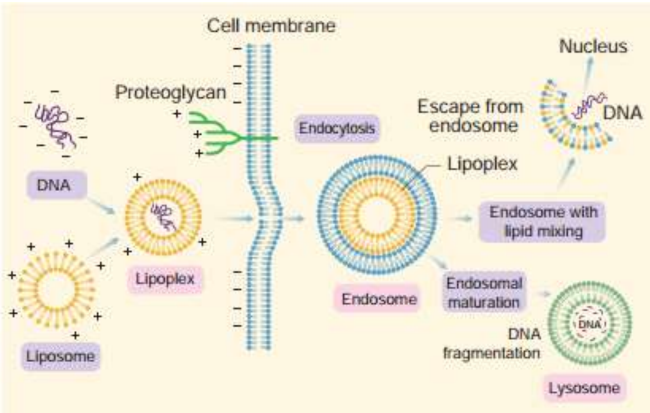

Fig. 5: Liposome-mediated gene transfer.

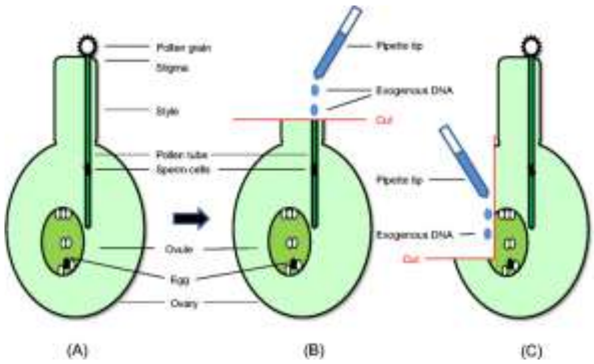

Fig. 6: Pollen tube pathway method.

IV

TOLERANCE OF TRANSGENIC CROPS IN DIFFERENT ENVIRONMENTAL CONDITIONS

- **Insect-Resistant Transgenic Crops**

Insect-resistant crops contain genes like the cry gene from Bacillus thuringiensis (Bt), which produce Cry proteins toxic to insects. This technology has been successfully used in crops like cotton, maize, and potato (Perlak et al., 1991; Adang et al., 1993).

- **Herbicide-Tolerant Transgenic Crops**

Herbicide-tolerant crops, such as glyphosate-tolerant soybeans, contain genes like cp4epsps, allowing them to survive applications of non-selective herbicides (Tabashnik et al., 1993).

- **Abiotic Stress-Tolerant Transgenic Crops**

Transgenic crops are developed to tolerate abiotic stresses like drought and salinity by altering their metabolism and activating stress response mechanisms (Raza et al., 2019).

- **Disease-Resistant Transgenic Crops**

Disease-resistant crops are engineered to resist pathogens like nematodes, fungi, bacteria, and viruses through gene silencing techniques such as RNA interference (Tricoli et al., 1995).

V

ENVIRONMENTAL AND HEALTH IMPACTS OF GM CROPS (1996-2015)

- **Environmental Impact**

The adoption of genetically modified (GM) crops has led to significant environmental benefits. From 1996 to 2015, the use of GM insect-resistant (IR) and herbicide-tolerant (HT) technologies reduced pesticide spraying by 618.7 million kg (8.1%). This reduction has decreased the Environmental Impact Quotient (EIQ) by 18.6%, indicating a lower environmental burden from herbicide and insecticide use. Additionally, GM crops have facilitated reductions in fuel consumption and tillage, leading to decreased greenhouse gas emissions equivalent to removing 11.9 million cars from the road in 2015 (Brookes and Barfoot, 2018). However, the extensive reliance on glyphosate in GM HT crops has led to the development of glyphosate-resistant weeds. This has necessitated the adoption of integrated weed management strategies combining multiple herbicides, which has somewhat reduced the initial environmental benefits. Despite this, the combined use of GM HT and GM IR technologies continues to provide a net positive environmental impact compared to traditional farming practices (Bonny, 2016).

- **Environmental and Human Health Concerns**

Impact on Plant-Associated Microbes

- The introduction of GM crops has raised concerns about their effects on plant-associated microbiota, such as nitrogen-fixing bacteria, mycorrhizal fungi, and endophytic microbiota. These microbes are crucial for plant health and productivity. Current research indicates that transgenic plants generally do not negatively impact these microbial communities. However, minor shifts in endophytic populations have been observed, highlighting the need for further investigation into the long-term ecological impacts (Moeser et al., 2017). The studies reveal that genetically modified endophytic bacteria generate minor alterations in the native endophytic population of the sweet orange Citrus sinensis. Preliminary results employing extracts from transgenic plants in tests using suitable fungal strains indicate that these plants have no effect on haploidization, mitotic crossing-over, mutation rate or chromosomal abnormalities (Bespalhok Filho et al., 2003).

Human Health Concerns

- First-generation GM crops were designed to provide alternative agronomic traits, such as herbicide and pest resistance, through the modification or transfer of specific genes. Second-generation GM crops aim to enhance nutritional and health-promoting properties. Concerns regarding human health include the potential toxicity of novel gene products, the expression of new allergens, unintended alterations in metabolic pathways, and variations in nutrient composition. Biotechnology-derived foods undergo more rigorous scrutiny compared to those produced through traditional breeding methods, addressing these concerns to some extent (Miller and Bradford, 2010).

Health Risks of GM Crops

- Toxicological evaluations of GM foods often suffer from limited exposure durations, insufficient to fully assess long-term biochemical changes or chronic health effects. There is a pressing need for more extensive and rigorous toxicity testing, including mutagenesis and carcinogenesis studies. Additionally, post-market surveillance for allergenicity, particularly in vulnerable populations, is essential. The potential presence of allergenic compounds, antibiotic resistance markers, and other harmful substances in GM crops underscores the importance of comprehensive safety assessments. While current literature generally supports the safety of GM foods, ongoing research is imperative to ensure their long-term safety for human consumption (Domingo, 2016). Other harmful compounds (such as increased levels of heavy metals) may be present in genetically modified crops, and they may not be "essentially similar" in terms of genome, proteome, and metabolome to unmodified crops. Another concern is the use of antibiotic-resistance genes as selectable markers in genetic engineering. This practice could potentially lead to the emergence of antibiotic-resistant bacterial strains, posing a significant public health risk due to the reduced efficacy of current antibiotics (Malarkey, 2003).

VI

POSITIVES AND NEGATIVES IMPACTS OF GM CROPS

- **ENVIRONMENTAL IMPACTS:**

Positives Impacts:

Reduced Pesticide Use: GM crops engineered for pest resistance, such as Bt cotton, have led to a significant reduction in the use of chemical pesticides, which is beneficial for the environment and biodiversity. This reduction in pesticide use not only lowers the ecological footprint but also decreases the exposure of non-target species to harmful chemicals (Klümper and Qaim, 2014).

Increased Yield: GM crops can be engineered to tolerate harsh conditions such as drought, salinity, and extreme temperatures, potentially leading to higher productivity on marginal lands. This capability is particularly crucial in addressing food security in regions affected by climate change (Carpenter, 2010).

Soil Health: Reduced need for tillage in herbicide-tolerant crops can lead to better soil health and reduced soil erosion. Conservation tillage practices enhance soil structure, water retention, and microbial activity, contributing to sustainable agriculture (Tillie and Rodríguez-Cerezo, 2010).

Negatives Impacts:

Biodiversity Concerns: The widespread adoption of GM crops can lead to a reduction in biodiversity as a result of monoculture practices. Monocultures can make ecosystems more vulnerable to pests and diseases (Wolfenbarger and Phifer, 2000).

Gene Flow: There is a risk of gene flow from GM crops to wild relatives, which could potentially create superweeds resistant to herbicides. This gene transfer can have unforeseen ecological consequences (Gassmann et al., 2011).

Non-target Organisms: GM crops, particularly those producing Bt toxin, might affect non-target organisms, including beneficial insects. The impact on these organisms could disrupt local ecosystems and food webs (Jayaraman, 2002).

- **SOCIAL IMPACTS:**

Positives Impacts:

Enhanced Food Security: By increasing crop yields and resilience, GM crops can contribute to food security, particularly in regions prone to food shortages (Qaim and De Janvry, 2005)

Labor Reduction: The use of herbicide-tolerant GM crops can reduce the need for manual weeding, thereby lowering labor requirements and costs. This can be particularly beneficial in regions where labor is scarce or expensive (Bennett et al., 2006).

Negatives Impacts:

Farmer Dependency: Farmers may become dependent on a few multinational companies for seeds, which can impact seed sovereignty and increase costs. This dependency can undermine traditional farming practices and seed sharing (Stone, 2011)

Socio-economic Inequality: Small-scale farmers might struggle to afford GM seeds and the associated inputs, potentially widening socio-economic gaps. This disparity can exacerbate poverty and limit access to new technologies for resource-poor farmers (Vitale et al., 2007).

- **ECONOMIC IMPACTS:**

Positives Impacts:

Increased Profitability: Higher yields and reduced input costs can lead to increased profitability for farmers growing GM crops. The economic benefits can support rural development and improve livelihoods (Bennett et al., 2006)

Market Access: Some GM crops can be tailored to meet specific market demands, potentially opening new economic opportunities. Innovations such as nutritionally enhanced crops can cater to health-conscious consumers (Stein and Rodríguez-Cerezo, 2010).

Negatives Impacts:

Market Restrictions: Certain markets, particularly in Europe, are resistant to GM products, which can limit export opportunities for farmers growing GM crops. This resistance can lead to economic losses and trade barriers (Tillie and Rodríguez-Cerezo, 2010)

Intellectual Property Issues: Patents on GM seeds can lead to higher seed prices and legal issues over seed saving and reuse. These intellectual property rights can restrict farmers' traditional practices and increase their costs (Demont et al., 2004)

- **PRODUCTIVITY IMPACTS:**

Positives Impacts:

Yield Gains: GM crops often show significant yield gains due to their resistance to pests and diseases, and their ability to thrive in suboptimal conditions. These gains are crucial for meeting the growing global food demand (Klümper and Qaim, 2014)

Resource Efficiency: GM crops can utilize water, nutrients, and other resources more efficiently, contributing to higher productivity per unit of input. This efficiency is vital for sustainable agricultural practices (Qaim and Zilberman, 2003)

Negatives Impacts:

Yield Plateaus: In some cases, yield gains from GM crops have plateaued, and the benefits have not always been consistent across different regions and conditions. This variability can limit the expected advantages of GM technology (Stone, 2011).

Resistance Development: Pests and weeds can develop resistance to GM traits, potentially leading to a resurgence of problems and the need for additional management strategies. This resistance can negate the benefits of GM crops and increase future control costs (Gassmann et al., 2011).

- **FARMER AND CONSUMER PERSPECTIVES ON GM CROPS**

Positives Impacts:

Acceptance and Trust: In regions where GM crops have demonstrated clear benefits, there is often higher acceptance and trust among farmers. This acceptance can drive wider adoption and improve overall agricultural productivity (Qaim and De Janvry, 2005)

Consumer Benefits: GM crops with enhanced nutritional profiles can offer direct benefits to consumers, such as Golden Rice enriched with Vitamin A. These benefits can address specific health issues and improve overall nutrition (Scott et al., 2018).

Negatives Impacts:

Public Perception: GM crops face significant opposition from segments of the public, often driven by concerns about safety, ethics, and environmental impacts. This opposition can hinder the adoption of GM technology and influence regulatory policies (Scott et al., 2018).

Regulatory Hurdles: Stringent regulations and approval processes in many countries can delay the adoption and commercialization of GM crops. These hurdles can increase development costs and limit the availability of beneficial technologies (Stein and Rodríguez-Cerezo, 2010)

VII
CURRENT PERSPECTIVES ON GENETICALLY MODIFIED CROPS AND DETECTION METHODS

In the agri-biotech industry, genetically modified (GM) crops are the most widely adopted products. This market penetration should provide a long-term foundation for maintaining food security for the world's rising population. The increasing pace of adoption of genetic engineering technology by farmers globally underscores the successful completion of two decades of commercial GM crop production (1996–2015). The requirement for reliable and sensitive detection methods for tracing and labeling genetically modified organisms in the food/feed chain has become increasingly important since the introduction of multiple traits stacked together in GM crops for combined herbicide tolerance, insect resistance, drought tolerance or disease resistance. Furthermore, numerous countries have established GM content thresholds that activate legally mandatory labeling schemes. In many countries (such as China, the EU, Russia, Australia, New Zealand, Brazil, Israel, Saudi Arabia, Korea, Chile, Philippines, Indonesia, Thailand), GM crop labeling is required, whereas in Canada, Hong Kong, the United States, South Africa, and Argentina, voluntary labeling schemes are in place. The rapid acceptance of GM crops has sparked debate, and it is critical to address these concerns by implementing appropriate regulatory mechanisms for the detection of GM crops. Whole genome sequencing employing next-generation sequencing (NGS) technologies gives an enhanced approach of detecting genetically modified organisms and foods/feeds in GM crops, although DNA-based detection methods have been successful (Gupta et al., 2022).

VIII

GM CROPS – CURRENT STATUS AND FUTURE ASPECTS

By introducing advantageous foreign gene(s) or inhibiting the expression of endogenous gene(s) in crop plants, genetic engineering and plant transformation have played a critical role in crop improvement. Herbicide tolerance, insect resistance, abiotic stress tolerance, disease resistance, and nutritional improvement are all qualities seen in genetically modified crops (Kumar et al., 2020). Approximately 525 transgenic events in 32 crops have been approved for cultivation in various parts of the world to date. Transgenic technology has been found to boost crop yields, reduce pesticide and insecticide use, lower CO_2 emissions and lower crop production costs. However, widespread adoption of transgenic crops containing foreign genes is hampered by concerns about human toxicity and allergenicity as well as potential environmental dangers such as gene flow, deleterious effects on non-target organisms, and weed and insect resistance evolution. Alternative technologies such as cisgenesis, intragenesis, and, most recently, genome editing have been adopted in response to these problems. Some of these alternative methods can be used to develop crop plants that are free of any alien genes; as a result, such crops are projected to have higher consumer acceptance and receive speedier regulatory approvals than transgenic crops (Waltz, 2015).

IX
STATUS OF RESEARCH, REGULATIONS AND CHALLENGES FOR GM CROPS IN INDIA

India experienced a significant agricultural transformation during the Green Revolution in the 1970s, leading to self-sufficiency in wheat and rice production. However, in the 21st century, climate change and increasing population pressures have posed new challenges. The resurgence of global hunger necessitates sustainable agriculture and collective efforts from all stakeholders to eliminate hunger and malnutrition by 2030 (FAO, IFAD, UNICEF, WFP, and WHO).

Genetically Modified (GM) crops, created through the transfer of genes for specific traits using laboratory techniques, have become a focal point in agricultural biotechnology. The first commercially successful transgenic fruit crop was the 'FlavrSavr' tomato, followed by numerous other GM food and non-food crops worldwide. Over the last three decades, advancements in biotechnology have led to the development and release of GM crops with novel traits for commercial agriculture (Raman, 2017). In India, research on GM crops has been ongoing for over two decades across various institutes, focusing on traits such as pest resistance, drought tolerance, and enhanced nutritional quality.

STATUS OF GM CROPS IN INDIA

In 2002, India saw a paradigm shift with the release of Bt cotton, a genetically engineered crop for insect resistance, approved by the Genetic Engineering Appraisal Committee (GEAC). This marked a significant milestone in India's GM crop research and deregulation, transforming the cotton industry. The adoption of Bt cotton has since grown exponentially, making India the second-largest producer and a leading exporter of cotton globally. As of 2012, approximately 7.2 million farmers cultivated Bt cotton on 10.8 million hectares, accounting for 93% of India's total cotton area, producing around 40 million bales by 2014 (ISAAA, 2014).

Despite this success, Indian agriculture still faces significant challenges. Approximately 70% of the population relies on agriculture, yet many farmers remain in poor economic conditions. Although the current government has shown some interest in GM field testing, state governments have been hesitant. There is an urgent need to enhance agricultural productivity to ensure food and nutrition security for the growing population. Embracing GM technology could lead to higher yield crops that are pest-resistant and thrive in harsh environments (James, 2013).

Research on GM crops in India includes over 20 crops in various stages of development and field trials, such as rice, wheat, maize, brinjal, potato, and mustard. The Indian Council of Agricultural Research (ICAR) plays a significant role in these efforts, focusing on genetic modification to improve crop traits (ICAR, 2022).

X

REGULATIONS

India's regulation of biotechnology products began in 1982 with the establishment of the National Biotechnology Board, later converted to the Department of Biotechnology (DBT) in 1986. The regulatory framework for GMOs and their products is governed by the 1989 Rules under the Environment Protection Act of 1986, administered by the Ministry of Environment, Forest and Climate Change (MoEF and CC).

The Genetic Engineering Appraisal Committee (GEAC), the highest regulatory body under the MoEF and CC, oversees the approval of large-scale GMO use, environmental release, and field applications. Key legislation includes the Environment Protection Act (1986), the Seed Act (1966), the Seeds (Control) Order, and the Food Safety and Standard Act (2006), which regulate the development, environmental release, and commercialization of GM crops (GEAC, 2023).

XI
CHALLENGES AND WAY FORWARD

Genetically modified (GM) crops present a viable solution to many of the pressing challenges faced by global agriculture today, including climate change, population growth, and diminishing arable land. These crops offer enhanced productivity, quality, and resistance to various stresses, aligning with the principles of sustainable agriculture: environmental protection, human health enhancement, and economic improvement. To harness the full potential of GM crops, it is imperative to establish and adhere to robust biosafety guidelines at all stages of their development and release. Comprehensive risk assessments, particularly focusing on gene flow, out-crossing, invasiveness, and effects on non-target organisms, are crucial for ensuring environmental and health safety.

Advanced molecular techniques, such as genome editing through CRISPR/Cas9, provide promising alternatives to traditional GM methods by improving crop traits without introducing foreign genes. This approach can address many public concerns and contribute significantly to achieving Sustainable Development Goals (SDGs) such as eradicating hunger and improving food security. Despite the potential benefits, public scepticism and regulatory challenges remain significant barriers to the widespread adoption of GM crops. Therefore, the scientific community and agricultural industries must invest in transparent communication and education to build public trust and counter misinformation. Strengthening regulatory frameworks and ensuring their efficient implementation through government agricultural bodies are essential steps towards broader acceptance.

Global collaboration and strategic innovation are key to leveraging the benefits of GM crops. By developing and adhering to a global risk alleviation strategy and effectively communicating with growers, the agricultural sector can ensure the substantial adoption of GM crops. This will not only boost global productivity and profitability but also contribute to a sustainable and food-secure future. GM crops have the potential to play a pivotal role in addressing global agricultural challenges and advancing sustainable development. Through strategic use of genome editing tools, robust regulatory practices, and transparent communication, GM crops can significantly enhance food security, human health, and environmental sustainability. The future of GM crops, particularly in regions like India, is promising, with ongoing research and field trials indicating their potential for significant agricultural advancements and global impact.

REFERENCES

Adang, M. J., Brody, M. S., Cardineau, G., Eagan, N., Roush, R. T., Shewmaker, C. K., Jones, A., Oakes, J. E., and McBride, K. E. (1993). The reconstruction and expression of a Bacillus thuringiensis cryIIIA gene in protoplasts and potato plants. Plant Molecular Biology, 21(6), 1131-1145.

Aldemita, R. R., Reano, I. M. E., Solis, R. O., and Hautea, R. A. (2015). Trends in global approvals of biotech crops (1992-2014). GM Crops and Food: Biotechnology in Agriculture and the Food Chain, 6(3), 150-166.

Bennett, R., Morse, S., and Ismael, Y. (2006). The economic impact of genetically modified cotton on South African smallholders: Yield, profit, and health effects. Journal of Development Studies, 42(4), 662-677.

Bespalhok Filho, J. C., Kobayashi, A. K., Pereira, L. F., Galvão, R. M., and Vieira, L. G. (2003). Transient gene expression of beta-glucuronidase in citrus thin epicotyl transversal sections using particle bombardment. Brazilian Archives of Biology and Technology, 46(1), 1-6.

Bonny, S. (2016). Genetically modified herbicide-tolerant crops, weeds, and herbicides: Overview and impact. Environmental Management, 57, 31-48.

Brookes, G., and Barfoot, P. (2018). Environmental impacts of genetically modified (GM) crop use 1996–2016: Impacts on pesticide use and carbon emissions. GM Crops and Food, 9(3), 109-139.

Carpenter, J. E. (2010). Peer-reviewed surveys indicate positive impact of commercialized GM crops. Nature Biotechnology, 28(4), 319-321.

Crossway, A., Oakes, J. V., Irvine, J. M., Ward, B., Knauf, V. C., and Shewmaker, C. K. (1986). Integration of foreign DNA following microinjection of tobacco mesophyll protoplasts. Molecular and General Genetics, 202(1), 179-185.

Dekeyser, R. A., Claes, B., De Rycke, R. M. U., Habets, M. E., Van Montagu, M. C., and Caplan, M. C. (1990). Transient gene expression in intact and organized rice tissues. The Plant Cell, 2(7), 591-601.

Delaney, B. (2015). Safety assessment of foods from genetically modified crops in countries with developing economies. Food and Chemical Toxicology, 86, 132-143.

Demont, M., Wesseler, J., and Tollens, E. (2004). Biodiversity versus transgenic sugar beet: The one Euro question. European Review of Agricultural Economics, 31(1), 1-18.

Domingo, J. L. (2016). Safety assessment of GM plants: An updated review of the scientific literature. Food and Chemical Toxicology, 95, 12-18.

Fabrick, J. A., Li, X., Carrière, Y., and Tabashnik, B. E. (2023). Molecular genetic basis of lab- and field-selected Bt resistance in pink bollworm. Insects, 14(2), 201.

FAO, IFAD, UNICEF, WFP, & WHO. (2020). The state of food security and nutrition in the world 2020: Transforming food systems for affordable healthy diets. Food and Agriculture Organization of the United Nations.

Fisk, H. J., and Dandekar, A. M. (2005). Electroporation: Introduction and expression of transgenes in plant protoplasts. In J. F. Kayser and H. J. Fisk (Eds.), Methods in Molecular Biology, 286, 79-90)

Gassmann, A. J., Petzold-Maxwell, J. L., Keweshan, R. S., and Dunbar, M. W. (2011). Field-evolved resistance to Bt maize by western corn rootworm. PLoS ONE, 6(7), e22629.

Genetic Engineering Appraisal Committee (GEAC). (2023). Regulatory framework for genetically modified organisms (GMOs) in India. Ministry of Environment, Forest and Climate Change (MoEF&CC).

Godfray, H. C. J., and Garnett, T. (2014). Food security and sustainable intensification. Philosophical Transactions of the Royal Society B: Biological Sciences, 369(1639), 20120273.

Gruere, G. P., and Sengupta, D. (2011). Bt cotton and farmer suicides in India: An evidence-based assessment. Journal of Development Studies, 47(2), 316-337.

Guardian. (2016). Plants genetically modified to boost photosynthesis produce greater yields, study shows. Retrieved from https://www.theguardian.com/science/2016/nov/17/plants-genetically-modified-to-boost-photosynthesis-produce-greater-yields-study-shows

Gupta, P., Ranjan, S., and Suresh, M. (2022). Advances in detection methods for genetically modified crops: A review. Journal of Agricultural and Food Chemistry, 70(3), 634-652.

Gupta, S., Kumar, A., Patel, R., and Kumar, V. (2021). Genetically modified crop regulations: Scope and opportunity using the CRISPR-Cas9 genome editing approach. Molecular Biology Reports, 48(6), 4851-4863.

Hooykaas, P. J. J., and Schilperoort, R. A. (1985). The Ti-plasmid of Agrobacterium tumefaciens: A natural genetic engineer. Trends in Biochemical Sciences, 10(8), 307-309.

Indian Council of Agricultural Research (ICAR). (2022). Research and development of genetically modified crops in India.

International Service for the Acquisition of Agri-biotech Applications (ISAAA). (2019). Bt cotton in India: A status report. Retrieved from https://www.isaaa.org/resources/publications/briefs/61/default.asp

James, C. (2013). Global status of commercialized biotech/GM crops: 2013. ISAAA Brief No. 46. ISAAA: Ithaca, NY.

Jayaraman, K. S. (2002). Bt cotton controversy: Researchers identify problems, regulatory loopholes. Nature Biotechnology, 20(10), 1069-1070.

Jogdand, S. N. (2006). Gene Biotechnology (2nd ed.). Himalaya Publishing House.

Kiranmai, C., Pullaiah, T., and Rajam, M. V. (2021). Genetically modified brinjal (Solanum melongena L.) and beyond. In C. Pullaiah (Ed.), Genetically Modified Crops (pp. 31-52). Springer.

Klein, R. M., Wolf, E. D., Wu, R., and Sanford, J. C. (1992). High velocity microprojectiles for delivering nucleic acids into living cells 1987. BioTechnology, 24(3), 384-386.

Klümper, W., and Qaim, M. (2014). A meta-analysis of the impacts of genetically modified crops. PloS one, 9(11), e111629.

Kranthi, K. R., and Stone, G. D. (2020). Long-term impacts of Bt cotton in India. Nature Plants, 6(3), 188-196.

Krattiger, A. F. (1997). Insect resistance in crops: A case study of Bacillus thuringiensis (Bt) and its transfer to developing countries. ISAAA Briefs No. 2. ISAAA: Ithaca, New York.

Kumar, H., and Kumar, V. (2004). Tomato expressing Cry1A(b) insecticidal protein from Bacillus thuringiensis protected against tomato fruit borer, Helicoverpa armigera (Hübner) (Lepidoptera: Noctuidae) damage in the laboratory, greenhouse and field. Crop Protection, 23(2), 135-139.

Kumar, K., Gambhir, G., Dass, A., Tripathi, A. K., Singh, A., Jha, A. K., Yadava, P., Choudhary, M., and Rakshit, S. (2020). Genetically modified crops: Current status and future prospects. Planta, 251(4), 91.

Kumar, K., Gambhir, G., Dass, A., Tripathi, A. K., Singh, A., Jha, A. K., ... and Rakshit, S. (2020). Genetically modified crops: current status and future prospects. Planta, 251(4), 91.

Malarkey, T. (2003). Human health concerns with GM crops. Journal of Environmental Science and Health, 21(4), 319-344.

Malarkey, T. (2003). Human health concerns with GM crops. Mutation Research/Reviews in Mutation Research, 544(2-3), 217-221.

McGaughey, W. H., and Whalon, M. E. (1992). Managing insect resistance to Bacillus thuringiensis. Science, 258(5087), 1451-1455.

Meadows, M. P. (1993). Bacillus thuringiensis in the environment: Ecology and risk assessment. In P. F. Entwistle, J. S. Cory, M. J. Bailey, and S. Higgs (Eds.), Bacillus thuringiensis, an Environmental Biopesticide: Theory and Practice (pp. 193-220). Wiley.

MHellmich, R. L., and Hellmich, K. A. (2012). Use and impact of Bt maize. Nature Education Knowledge, 3(5), 4.

Miller, H. I., and Bradford, K. J. (2010). The regulatory bottleneck for biotech crops. Nature Biotechnology, 28(4), 363-369.

Moeser, A., Salles, J. F., Smalla, K., and van Elsas, J. D. (2017). The influence of transgenic plants on naturally occurring plant-associated bacteria. Applied and Environmental Microbiology, 83(4), e03362-16.

Natarajan, S., and Sinha, P. (2022). Status and regulatory issues of genetically modified rice in India. Journal of Environmental Biology, 43(2), 265-273.

National Research Council. (2002). Environmental effects of transgenic plants: the scope and adequacy of regulation. National Academies Press.

Nester, E. W., Altosaar, I., and Stotzky, G. (2002). 100 years of Bacillus thuringiensis: A critical scientific assessment. American Academy of Microbiology Colloquium Report. Based on Colloquium, Ithaca.

Nyika, R. S., Yadav, J., Mackolil, S. J., GRP Workie, E., Ragupathy, R., and Ramasundaram, P. (2022). Genetically modified foods: Bibliometric analysis on consumer perception and preference. GM Crops and Food, 13(1), 65-85.

Perlak, F. J., Fuchs, R. L., Dean, D. A., McPherson, S. L., and Fischhoff, D. A. (1991). Modification of the coding sequence enhances plant expression of insect control protein genes. Proceedings of the National Academy of Sciences, USA, 88(8), 3324-3328.

Pradhan, S., and Singh, Y. V. (2021). GM mustard in India: Economic and ecological implications. Agricultural Economics Research Review, 34(1), 1-12.

Prakash, C. S., and Jayaraman, K. S. (2010). Bt rice: A potential GM crop for India. Current Science, 98(4), 424-431.

Qaim, M., and De Janvry, A. (2003). Genetically modified crops, corporate pricing strategies, and farmers' adoption: The case of Bt cotton in Argentina. American Journal of Agricultural Economics, 85(4), 814-828.

Qaim, M., and De Janvry, A. (2005). Bt cotton and pesticide use in Argentina: Economic and environmental effects. Environment and Development Economics, 10(2), 179-200.

Qaim, M., and Zilberman, D. (2003). Yield effects of genetically modified crops in developing countries. Science, 299(5608), 900-902.

Raman, R. (2017). The impact of genetically modified (GM) crops in modern agriculture: A review. GM Crops and Food: Biotechnology in Agriculture and the Food Chain, 8(4), 195-208.

Rani, S. J., and Usha, R. (2013). Transgenic plants: Types, benefits, public concerns and future. Journal of Pharmacy Research, 6(8), 879-883.

Raza, A., Razzaq, A., Mehmood, S. S., Zou, X., Zhang, X., Lv, Y., and Xu, J. (2019). Impact of climate change on crops adaptation and strategies to tackle its outcome: A review. Plants, 8(2), 34.

Sanahuja, G., Banakar, R., Twyman, R. M., Capell, T., and Christou, P. (2011). Bacillus thuringiensis: A century of research, development and commercial applications. Plant Biotechnology Journal, 9(3), 283-300.

Sanford, J. C., Klein, T. M., Wolf, E. D., and Allen, N. (1987). Delivery of substances into cells and tissues using a particle bombardment process. Journal of Particulate Science and Technology, 5(1), 27-37.

Schouten, H. J., Krens, F. A., and Jacobsen, E. (2006). Do cisgenic plants warrant less stringent oversight? Nature Biotechnology, 24(7), 753.

Scott, S. E., Inbar, Y., Wirz, C. D., Brossard, D., and Rozin, P. (2018). An overview of attitudes toward genetically engineered food. Annual Review of Nutrition, 38, 459-479.

Shiva, V. (2010). The GMO Emperor Has No Clothes: A Global Citizens Report on the State of GMOs. Navdanya International.

Song, X., Gu, Y., and Qin, G. (2007). Application of a transformation method via the pollen-tube pathway in agriculture molecular breeding. Life Science Journal, 4(1), 77-79.

Southgate, E. M., Davey, M. R., Power, J. B., and Merchant, R. (1995). Factors affecting the genetic engineering of plants by microprojectile bombardment. Biotechnology Advances, 13(4), 631-657.

Stein, A. J., and Rodríguez-Cerezo, E. (2010). International trade and the global pipeline of new GM crops. Nature Biotechnology, 28(1), 23-25.

Stone, G. D. (2011). Field versus farm in Warangal: Bt cotton, higher yields, and larger questions. World Development, 39(3), 387-398.

Tabashnik, B. E., Finson, N., Johnson, M. W., and Moar, W. J. (1993). Resistance to toxins from Bacillus thuringiensis subsp. kurstaki causes minimal cross-resistance to B. thuringiensis subsp. aizawai in diamondback moth (Lepidoptera: Plutellidae). Applied and Environmental Microbiology, 59(5), 1332-1335.

Thomas, A., and Mathew, M. (2022). Genetically modified rubber for abiotic stress tolerance. Journal of Rubber Research, 25(3), 205-216.

Tillie, P., and Rodríguez-Cerezo, E. (2010). Markets for non-genetically modified, identity-preserved soybean in the EU. JRC Scientific and Technical Reports.

Tricoli, D. M., Carney, K. J., Russell, P. F., McMaster, J. R., and Grof, D. W. (1995). Field evaluation of transgenic squash containing single or multiple virus coat protein gene constructs for resistance to cucumber mosaic virus, watermelon mosaic virus 2 and zucchini yellow mosaic virus. Nature Biotechnology, 13(13), 1458-1465.

Vitale, J., Boyer, T., Uaiene, R., and Sanders, J. (2007). The economic impacts of introducing Bt technology in smallholder cotton production systems of West Africa: A case study from Mali. AgBioForum, 10(2), 71-84.

Waltz, E. (2015). Beating the GM trait slump. Nature Biotechnology, 33(8), 811-812.

Wolfenbarger, L. L., and Phifer, P. R. (2000). The ecological risks and benefits of genetically engineered plants. Science, 290(5499), 2088-2093.

Zhu, Z., Sun, B., Liu, C., Xiao, G., and Li, X. (1993). Transformation of wheat protoplasts mediated by cationic liposome and regeneration of transgenic plantlets. Chinese Journal of Biotechnology, 9(4), 257-261.