**Transforming Indian Agriculture: The Policy and Impact Landscape of Genetically modified (GM) Technologies**

**ABSTRACT**

Genetically modified (GM) crops present India with a transformative opportunity to address pressing challenges in food security, climate adaptation, and agricultural sustainability. This review critically examines the scientific advances, historical development, regulatory frameworks, socio-economic impacts, and ethical debates shaping the adoption of GM crops in India. While Bt cotton has emerged as the country’s primary GM success, covering over 90% of national cotton acreage and significantly improving yields and farmer incomes, efforts to commercialise other GM crops such as Bt brinjal and GM mustard have encountered persistent regulatory delays, political opposition, and public scepticism. The paper explores the evolving roles of the Genetic Engineering Appraisal Committee (GEAC) and the Department of Biotechnology (DBT), highlighting how recent reforms especially the 2022 guidelines for genome-edited crops reflect a policy shift toward innovation-friendly regulation. In addition, it addresses critical socio-economic and ethical considerations, including smallholder access to technology, seed sovereignty, intellectual property rights, environmental risks, and consumer choice. Looking ahead, advances in genome editing, synthetic biology, and multi-omics approaches hold immense promise for developing stress-tolerant, nutrient-enriched, and regionally adapted crops tailored to India’s diverse agro-ecological zones. This review synthesises current scientific, regulatory, and socio-political evidence to provide researchers, policymakers, and stakeholders with actionable insights for creating a transparent, inclusive, and science-based roadmap for the responsible deployment of GM technologies in India’s agricultural future.

***Keywords:*** *Genetically modified, Bt cotton, Bt brinjal, GM mustard, GEAC, genome editing, synthetic biology, multi-omics*

1. **INTRODUCTION**

Genetically modified (GM) crops, also referred to as transgenic crops, are developed through the precise alteration of genetic material using modern biotechnological tools to incorporate specific, desirable traits. These may include resistance to insect pests, tolerance to herbicides, resistance to viral diseases, enhanced nutritional content, and adaptability to abiotic stressors such as drought and salinity. Unlike conventional breeding methods that rely on cross-compatible species and lengthy breeding cycles, genetic engineering enables the targeted transfer of genes even across unrelated species, thus significantly accelerating the pace and scope of crop improvement (James, 2010; Qaim et al., 2020). The development and deployment of GM crops have been motivated by a confluence of global challenges an increasing world population projected to reach nearly 10 billion by 2050, diminishing arable land due to urban expansion and degradation, volatile climate patterns, and the imperative to reduce chemical inputs in agriculture. In this context, GM technology is viewed as a pivotal innovation capable of enhancing agricultural productivity, reducing environmental footprints, and contributing to food and nutritional security (Zaidi et al., 2019). GM crops are categorized into major functional groups based on their traits: herbicide-tolerant, insect-resistant, dual herbicide and insect-resistant, and virus-resistant varieties. These crops represent a shift from reactive crop protection to preventive and genetically embedded solutions.

Since their commercial introduction in 1996, GM crops have witnessed rapid global adoption. According to the International Service for the Acquisition of Agri-biotech Applications (ISAAA, 2019), GM crops were cultivated on over 190 million hectares across 29 countries as of 2019. The largest adopters include the United States, Brazil, Argentina, Canada, and India. The most widely grown GM crops globally are soybean, maize, cotton, and canola primarily engineered for insect resistance and herbicide tolerance. The benefits attributed to these crops include increased yield potential, reduced reliance on chemical pesticides, improved farm profitability, and better adaptability to changing environmental conditions (Brookes & Barfoot, 2020). In India, the only GM crop approved for commercial cultivation thus far is Bt cotton, introduced in 2002. This transgenic crop contains a gene from the soil bacterium Bacillus thuringiensis (Bt), which enables the plant to produce insecticidal proteins effective against bollworm infestations. Bt cotton adoption has been widespread, now covering more than 90% of India's cotton-growing area. Empirical studies have linked its adoption to significant reductions in pesticide use, improvements in crop yields, and increases in farmer income (Kambhampati et al., 2017; Choudhary & Gaur, 2021). However, the path for other GM crops such as Bt brinjal and GM mustard has been fraught with delays and controversies, despite positive assessments from scientific regulatory bodies such as the Genetic Engineering Appraisal Committee (GEAC) (Kumar et al., 2020).

The debate surrounding GM crops in India is shaped not only by scientific and agronomic evidence but also by a web of socio-political, economic, and ethical considerations. Proponents argue that GM technology is indispensable for achieving food and nutritional security in the face of biotic and abiotic stresses, particularly under climate change scenarios. Moreover, emerging GM innovations, including RNA interference (RNAi) technology and genome editing via CRISPR/Cas systems, hold the promise of even greater precision and public acceptance due to their reduced transgenic footprint. On the other hand, critics raise valid concerns regarding potential ecological risks, including gene flow to wild relatives, development of pest resistance, impacts on non-target organisms, and biodiversity loss. Additionally, issues of seed sovereignty, corporate control over agricultural biotechnology, and the perceived lack of transparency in regulatory decision-making processes have fueled public apprehension and resistance. The polarized nature of the GM debate in India is further exacerbated by gaps in public awareness, limited farmer education, and the circulation of misinformation, which collectively hinder informed discourse (Qaim et al., 2020).

India’s regulatory framework for GM crops is primarily overseen by the GEAC under the Ministry of Environment, Forest and Climate Change (MoEFCC), which is responsible for evaluating environmental and biosafety risks before approving the release of GM organisms. Despite the structured multi-tier evaluation process, regulatory inertia, legal battles, and public protests have impeded the commercial deployment of several GM crops beyond Bt cotton. The regulatory journey of GM mustard, for instance, reflects the broader institutional and ideological challenges that influence biotechnology governance in India. Given India’s diverse agro-ecological zones, smallholder-dominated farming systems, and democratic policy landscape, the implications of GM crop adoption are uniquely complex. Therefore, a comprehensive, evidence-based assessment is necessary to evaluate the true potential and risks associated with GM crops in the Indian context. This review aims to synthesize current scientific literature, field-level evidence, regulatory perspectives, and socio-political dynamics to offer a balanced and multidimensional analysis of GM crop deployment in India.

Specifically, the review will explore:

* The agronomic and economic impacts of GM crops, with a focus on yield performance, input cost efficiency, and farmer profitability.
* The ecological consequences, including biosafety, resistance management, and environmental sustainability.
* The structure and effectiveness of India’s regulatory framework, along with the influence of civil society and public perception.
* The future of GM technology in India, considering recent advances in genome editing and the relevance of GM crops to climate-resilient agriculture and nutritional enhancement.
1. **Advances in Genetic Modification Techniques and Their Global Applications in Agriculture**

Feeding a rapidly growing global population—projected to reach nearly 10 billion by 2050—presents unprecedented challenges to agricultural systems worldwide (Godfray et al., 2010). These include limited arable land, climate change-induced stresses, declining soil fertility, and the need to reduce chemical inputs while ensuring food and nutritional security (Foley et al., 2011). In this context, biotechnology has emerged as a transformative force in modern agriculture, offering precision tools for crop improvement far beyond the capabilities of conventional breeding (Tester et al., 2010). Among these tools, genetic modification (GM) stands out for its ability to introduce targeted changes in plant genomes to enhance traits such as yield, pest resistance, abiotic stress tolerance, and nutritional quality (Qaim et al., 2020).

Genetic modification refers to the direct manipulation of an organism's DNA using biotechnological methods to develop novel traits or enhance existing ones (Gelvin et al., 2003). This review encompasses a broad spectrum of GM techniques, from traditional transgenic approaches to cutting-edge genome editing tools such as CRISPR/Cas systems, RNA interference (RNAi), and cisgenesis (Adli, 2021). These technologies have revolutionized crop development and are increasingly integrated into global agricultural strategies (Jaganathan et al., 2018). The development of genetically modified crops relies on a variety of transformation and editing methods, each with specific applications, benefits, and limitations. These techniques can be broadly categorized into classical transformation methods and advanced genome editing technologies. Genetic modification (GM) of crops entails the precise and targeted alteration of plant genomes to confer traits that enhance productivity, stress tolerance, or nutritional composition (Tester et al., 2010). Unlike conventional breeding approaches constrained by species compatibility and long breeding cycles, GM techniques offer the advantage of introducing genes across species barriers with high specificity and efficiency (Gelvin et al., 2003). A suite of molecular, physical, and biological techniques enables transformation across a wide array of crop species, depending on the trait, species, and desired stability of expression (Jaganathan et al., 2018).

* 1. **Agrobacterium-Mediated Transformation**

Agrobacterium-mediated transformation is among the most commonly employed methods for gene transfer in dicotyledonous crops (Gelvin et al., 2003). It leverages Agrobacterium tumefaciens, a soil bacterium, and its Ti plasmid, wherein the tumor-inducing genes are replaced by a gene of interest (GOI) and a selectable marker. The GOI is inserted into the plant genome through the T-DNA region, resulting in stable transformation (Hiei et al., 1994). Initially limited to dicots, this method has been optimized for use in monocots such as rice and maize through innovations in tissue culture and vector design.

* 1. **Particle Bombardment (Biolistics)**

This physical method, also known as the gene gun technique, propels DNA-coated metal microparticles (typically gold or tungsten) into plant cells using high-pressure helium (Sanford et al., 2000). The DNA dissociates from the particles and integrates into the nuclear or plastid genome. Widely used in monocots and recalcitrant species, it allows transformation irrespective of species compatibility and enables chloroplast transformation, which is maternally inherited and minimizes transgene escape (Maliga et al., 2004).

 **2.3 Electroporation and PEG-Mediated Transformation**

These techniques are commonly applied in protoplast systems—plant cells with cell walls enzymatically removed (Davey et al., 2005). Electroporation uses a brief electric pulse to create transient membrane pores, facilitating DNA entry, while polyethylene glycol (PEG) induces DNA uptake via membrane destabilization. Though offering high transformation efficiency, the challenge of regenerating whole plants from protoplasts limits the routine use of these methods in many major crops.

 **2.4 RNA Interference (RNAi) Technology**

RNA interference is a post-transcriptional gene silencing mechanism triggered by the presence of double-stranded RNA (dsRNA) (Baulcombe et al., 2004). This dsRNA is processed into small interfering RNAs (siRNAs), which guide the degradation of complementary mRNA, effectively silencing the gene. RNAi technology has been utilized to develop traits such as resistance to viruses and nematodes, delay fruit ripening, and suppress undesirable metabolites.

**2.5 CRISPR/Cas-Based Genome Editing**

CRISPR/Cas systems, especially CRISPR/Cas9, have emerged as transformative tools for targeted genome editing (Jaganathan et al., 2018). Guided by a synthetic RNA (gRNA), the Cas9 nuclease introduces site-specific double-strand breaks in the DNA, which are repaired by non-homologous end joining (NHEJ) or homology-directed repair (HDR), allowing for precise deletions, insertions, or replacements (Chen et al., 2019). This technology has been successfully applied in major crops including rice, wheat, tomato, and mustard for trait improvement (Adli, 2021).

**2.6 Cisgenesis and Intragenesis**

Cisgenesis involves the insertion of entire genes, including their regulatory elements, from a cross-compatible donor species into the host plant (Schouten et al., 2006). Intragenesis, by contrast, allows for the combination of genetic elements such as promoters and coding sequences from within the same gene pool. These methods avoid the introduction of foreign DNA and are considered more acceptable by the public and some regulatory frameworks (Gelvin et al., 2003). Variants such as base editing and prime editing further expand the editing toolkit. CRISPR has been used globally to create drought-tolerant rice, mildew-resistant wheat, and GABA-enriched tomatoes. It is widely regarded as the future of crop improvement due to its minimal off-target effects and regulatory advantages in some countries.

1. **Global Status and Adoption of GM Crops**

The global adoption of genetically modified (GM) crops has expanded significantly since their commercial introduction in the mid-1990s. As of the latest estimates, GM crops are cultivated on over 190 million hectares worldwide, with the majority concentrated in a handful of leading countries, including the United States, Brazil, Argentina, Canada, and India. These nations have embraced GM technologies primarily to enhance crop productivity, reduce dependency on chemical inputs, and improve resistance to biotic and abiotic stresses. The most widely adopted GM crops are soybean, maize, cotton, and canola, which have been engineered predominantly for traits such as herbicide tolerance, insect resistance, and disease resilience.

In the United States, which leads in GM crop cultivation, herbicide-tolerant soybean and insect-resistant maize dominate the landscape, contributing significantly to farm profitability and production efficiency. Brazil and Argentina have followed similar adoption patterns, driven by the need to sustain large-scale commercial agriculture. In Asia, India has successfully commercialized Bt cotton, which now accounts for over 90% of the country’s cotton acreage and has played a pivotal role in enhancing farmer incomes and reducing pesticide use. China and the Philippines have also made strides, particularly in papaya and maize, while Bangladesh has emerged as a pioneer in approving Bt brinjal for commercial cultivation.

The adoption of GM crops has yielded measurable agronomic, economic, and environmental benefits. Studies indicate substantial yield gains, improved pest control, and a significant reduction in pesticide use, which collectively support sustainability goals. Additionally, GM technologies have enabled farmers to adopt more conservation-oriented practices, such as reduced tillage, which lowers greenhouse gas emissions and improves soil health. Despite these advancements, the pace of GM crop adoption varies globally, influenced by national policies, public perception, and trade considerations. While some countries have fully embraced GM agriculture, others, particularly in the European Union and parts of Africa, maintain stringent regulatory barriers and public resistance that limit widespread deployment.

1. **Development of Genetically Modified (GM) Crops Over the Years**

In 1946, the modern genetic modification took place where the first discovery related to transfer of genetic material between different species took place. Since the first successful transformation of plant cells in the early 1980s, genetically modified (GM) crops have evolved from experimental curiosities into globally cultivated varieties with significant economic, environmental, and food security implications. This transformation has occurred in phases, each characterized by distinct technological breakthroughs, regulatory milestones, and shifts in public perception. The evolution of GM crops can be traced through three major chronological and technological stages: the foundational transgenic phase, the era of global commercialization, and the recent revolution in precision genome editing. Understanding this trajectory is essential to contextualizing current debates and future directions in biotechnology and sustainable agriculture.

**4.1 Transgenic Foundation Phase (1980s–1990s): Pioneering Genetic Engineering in Crops**

The early development of GM crops stemmed from advances in recombinant DNA technology that allowed for the insertion of foreign genes into plant genomes. The pioneering work by Fraley et al. (1983) marked the first successful stable transformation of plants, utilizing Agrobacterium tumefaciens to introduce a bacterial gene into tobacco. This breakthrough catalyzed the development of transformation techniques like Agrobacterium-mediated transformation, which became widely used in dicots (Gelvin et al., 2003), and particle bombardment, which enabled transformation in monocots (Sanford et al., 2000). The first commercial GM food crop, the Flavr Savr tomato, was introduced in 1994 and aimed to delay spoilage using antisense RNA to suppress a softening enzyme. Though not a commercial success, the Flavr Savr served as proof-of-concept and helped inform regulatory and consumer engagement models (Bruening et al., 2000).

**4.2 Commercial Expansion and Global Adoption (1996–2010): From Field Trials to Market Integration**

The commercialization of Bt cotton and glyphosate-tolerant soybean in the mid-1990s marked the beginning of a new era for GM crops. These first-generation traits conferred insect resistance through cry genes from Bacillus thuringiensis and herbicide tolerance through EPSPS gene modifications (James et al., 2010). By offering farmers solutions to reduce pest pressures and simplify weed management, GM crops quickly gained traction in North and South America, followed by Asia and Africa.

By 2010, GM crops were being cultivated on more than 148 million hectares globally (ISAAA et al., 2010). Key players included the United States, Brazil, Argentina, India, and Canada. The dominant GM crops—soybean, maize, cotton, and canola—were grown for both commercial and subsistence farming purposes. A growing body of evidence has confirmed the positive impact of GM crops on farm profitability and environmental outcomes, particularly in resource-constrained regions (Qaim et al., 2003; Finger et al., 2022). In India, the approval of Bt cotton in 2002 revolutionized cotton farming, especially for smallholders. The crop significantly reduced bollworm damage and pesticide usage, leading to improved economic returns and reduced occupational health risks for farmers (Choudhary et al., 2021). Despite these successes, political resistance and public skepticism slowed the commercialization of other GM crops such as Bt brinjal and GM mustard, despite favorable scientific reviews.

**4.3 Precision Genome Editing Era (2010–Present): The CRISPR Revolution**

The post-2010 era is characterized by the emergence of targeted genome editing technologies, including Zinc Finger Nucleases (ZFNs), Transcription Activator-Like Effector Nucleases (TALENs), and, most notably, the CRISPR/Cas system. CRISPR/Cas9 has become a paradigm-shifting tool due to its simplicity, specificity, and adaptability across species (Jaganathan et al., 2018; Chen et al., 2019). By enabling site-specific edits without the integration of foreign DNA, CRISPR has redefined the regulatory and ethical boundaries of genetic modification.

CRISPR-based interventions have already delivered crops with enhanced drought tolerance (for example, rice), resistance to powdery mildew (for example, wheat), and enriched micronutrient content (for example, GABA tomatoes) (Chen et al., 2019; Adli, 2021). The versatility of CRISPR has also enabled novel breeding strategies such as multiplex gene editing, base editing, and prime editing, which allow for complex trait engineering without lengthy breeding cycles. Many countries, including the U.S., Japan, and Argentina, have adopted regulatory frameworks that differentiate gene-edited crops from traditional GMOs. India is currently evaluating its regulatory stance; in 2022, the Department of Biotechnology proposed simplified rules for certain genome-edited crops, recognizing their potential under the broader goals of agricultural innovation and sustainability.

1. **Future Directions: Synthetic Biology, Omics Integration, and Climate Resilience**

Looking forward, the convergence of synthetic biology, multi-omics platforms, and AI-driven trait prediction is redefining the horizon for GM crop development. New frontiers include gene circuits for stress sensing, transgene-free biofortified crops, and crops engineered for carbon sequestration and nitrogen-use efficiency (Zaidi et al., 2019). Examples of ongoing research include iron-rich rice, zinc-enhanced wheat, and heat-tolerant legumes—developed not only for yield, but also for tackling malnutrition and climate extremes. Furthermore, the use of gene stacking (combining multiple traits) and tissue-specific promoters is improving trait specificity and expression efficiency. As global agriculture faces increasingly volatile climate scenarios, the role of next-generation GM crops in building resilient food systems is expected to expand. Public-private partnerships, transparent communication, and participatory regulatory reforms will be crucial to realizing the full potential of GM technology.

## **STATUS OF GM CROPS IN INDIA**

India’s journey with genetically modified (GM) crops reflects a complex interplay between scientific advancement, regulatory caution, public perception, and policy evolution. In 2002, the Genetic Engineering Approval Committee (GEAC) approved the commercial cultivation of Bt cotton, which had been genetically modified to withstand insect attacks. This move marked a significant turning point in the country's GM crop research, deregulation, and even the cotton industry. Since then, the world's production and cultivation of Bt cotton have increased dramatically. In a short period of 12 years, around 7.7 million farmers have adopted Bt cotton in India emerging as both the world's second-largest cotton producer and top exporter. India’s formal engagement with GM technology began in the early 1990s when the Department of Biotechnology (DBT) established biosafety guidelines for the regulation of genetically engineered organisms. This was followed by the formation of institutional bodies such as the Review Committee on Genetic Manipulation (RCGM) and the Genetic Engineering Appraisal Committee (GEAC) to oversee the testing and release of transgenic crops. The foundational legal framework for regulating GM organisms was set under the Environment Protection Act (1986), particularly the Rules of 1989, which remain in force (Kumar, 2015).

The first major milestone came in 2002, when Bt cotton was approved for commercial cultivation, making India the first country in the developing world to adopt a GM crop on a large scale. Bt cotton, developed by Mahyco in collaboration with Monsanto, incorporates cry1Ac and later cry2Ab genes from Bacillus thuringiensis, providing effective protection against bollworm. The rapid uptake of Bt cotton revolutionized India’s cotton sector. Within a decade, it covered over 90% of the cotton-growing area, contributing to increased yields, reduced pesticide usage, and improved farmer incomes (Choudhary et al., 2021; Qaim et al., 2003). However, over time, issues such as secondary pest outbreaks and resistance management challenges emerged, indicating the need for integrated pest management and newer transgenic technologies (Kambhampati et al., 2017). Encouraged by the success of Bt cotton, several public and private research institutions began developing GM varieties of food and vegetable crops. One of the most prominent was Bt brinjal, a transgenic variety developed by Mahyco in partnership with public-sector institutions. Following successful field trials and biosafety evaluations, the GEAC approved its commercial release in 2009. However, in 2010, the Ministry of Environment imposed an indefinite moratorium, citing insufficient consensus among stakeholders and the need for more inclusive consultations (Paarlberg et al., 2014). This decision marked a significant policy setback and shifted the trajectory of GM food crop development in India. Ironically, neighboring Bangladesh approved Bt brinjal in 2013 and has since witnessed positive farmer feedback and sustained cultivation. The debate around GM food crops intensified in subsequent years, particularly with the development of GM mustard (DMH-11) by the University of Delhi. The transgenic mustard hybrid uses the barnase-barstar-bar gene system to facilitate hybrid seed production, aiming to boost domestic oilseed productivity and reduce import dependency. After clearing biosafety and agronomic evaluations, GEAC recommended its approval in 2017 and again in 2022. Despite these endorsements, the final decision has been repeatedly delayed due to political hesitations and legal challenges (Kumar et al., 2020). As of 2024, GM mustard remains in regulatory limbo, symbolic of the larger impasse in India’s biotech policy for food crops.

In the 2010s, India also began exploring second-generation GM crops such as virus-resistant papaya, biofortified banana with enhanced provitamin A, and drought-tolerant chickpea. These crops are being developed by public-sector research institutions including the Indian Council of Agricultural Research (ICAR) and state agricultural universities, often in collaboration with international agencies. Many of these have completed field trials, but await regulatory and political clearance. A potential turning point arrived in 2022, when the Department of Biotechnology released new guidelines for genome-edited crops. These guidelines exempt SDN-1 and SDN-2 categories (site-directed nuclease-mediated edits that do not introduce foreign DNA) from the rigorous approval process required for transgenic GMOs (DBT, 2022). This decision brought India in alignment with progressive regulatory stances seen in countries like the U.S., Japan, and Argentina. CRISPR-based edits in crops like low-gluten wheat, virus-resistant tomatoes, and stress-tolerant rice are now being explored under these new norms (Jaganathan et al., 2018; Zaidi et al., 2019).

As of 2024, Bt cotton remains the sole GM crop commercially cultivated in India, despite the scientific readiness of other crops. The policy environment remains cautious, shaped by a mixture of scientific diligence, judicial interventions, and activist resistance. Public perception continues to be influenced by concerns over biosafety, corporate control, and lack of awareness, despite evidence supporting the agronomic and environmental benefits of GM crops (Finger et al., 2022). Meanwhile, genome editing offers a new paradigm one that could enable India to adopt advanced biotechnological solutions without the regulatory burdens and controversies historically associated with transgenics. India’s path forward will depend on institutional coherence, evidence-based policymaking, transparent risk communication, and broader societal dialogue. The integration of cutting-edge biotechnologies into Indian agriculture holds transformative potential but realizing it will require clarity of vision and courage of implementation.Timeline of GM Crop Development in India tabulated in Table 1.

**Table 1: Timeline of GM Crop Development in India**

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| --- | --- | --- |
| **Year** | **Milestone** | **Status / Release Location** |
| 1990 | First GM trials in India (tobacco and tomato). | Experimental trials in research institutes |
| 1996 | Field trials of Bt cotton begin. | Conducted in select ICAR and state agricultural universities |
| 2002 | Bt cotton approved for commercial use — first and only GM crop commercially cultivated. | Commercialized in Maharashtra, Gujarat, Andhra Pradesh, Punjab, etc. |
| 2006–2009 | Trials for Bt brinjal conducted by public and private institutes. | Conducted across multiple ICAR centers and states (e.g., Tamil Nadu, Bihar) |
| 2010 | Bt brinjal approved by GEAC but put on moratorium due to public opposition. | Approval withheld; moratorium enforced nationwide |
| 2016 | GM mustard (DMH-11) cleared by GEAC; held up by legal petitions. | Not released; pending Supreme Court litigation |
| 2022 | GEAC re-approves GM mustard for environmental release. | Cleared for limited environmental release by ICAR centers |
| 2023–2024 | GM mustard planted for confined field trials in select states under regulatory scrutiny. | Trials underway in Rajasthan, Punjab, Delhi, and Uttar Pradesh |

1. **Regulatory Frameworks and Policy Landscape for GM Crops in India**

The regulatory system governing genetically modified (GM) crops in India has developed through a complex interplay of scientific assessments, environmental safeguards, political considerations, and public sentiment (Kumar et al., 2020). As one of the world’s largest agricultural economies, India’s approach to GM regulation is uniquely shaped by its socio-economic diversity, smallholder-dominated farming systems, and biodiversity richness (Choudhary et al., 2021). While the commercial success of Bt cotton stands as India’s most notable example of GM crop adoption, the country’s experience with other GM crops has been marked by delays, political controversies, and legal challenges (Kambhampati et al., 2017).

India’s GM crop approval process is overseen by the Genetic Engineering Appraisal Committee (GEAC), under the Ministry of Environment, Forest and Climate Change, which conducts multi-level evaluations, including laboratory research, biosafety assessments, confined and open field trials, environmental impact assessments, and public consultations (Kumar et al., 2020). Complementary regulatory roles are played by the Review Committee on Genetic Manipulation (RCGM) under the Department of Biotechnology, responsible for overseeing the research phase, and the Food Safety and Standards Authority of India (FSSAI), which addresses food safety issues. India’s foundational biosafety rules were set out in the Rules for the Manufacture, Use, Import, Export, and Storage of Hazardous Microorganisms/Genetically Engineered Organisms or Cells (1989) under the Environment (Protection) Act, 1986 (MoEF, 2010). These rules laid the groundwork for one of the world’s strictest precautionary regulatory systems, requiring rigorous environmental and food safety evaluations before commercial approval (Kumar et al., 2020). However, as global biotechnology has evolved, concerns have emerged about the regulatory system’s ability to keep pace with scientific advances (Kambhampati et al., 2017).

Bt cotton, approved in 2002, is India’s only commercially cultivated GM crop and now covers over 90% of the country’s cotton area, delivering substantial gains in yield, reductions in pesticide use, and improvements in farm incomes (Choudhary and Gaur, 2021; Kambhampati et al., 2017). Despite these successes, efforts to commercialize other GM crops, such as Bt brinjal and GM mustard (DMH-11), have faced repeated setbacks. Bt brinjal, despite passing GEAC assessments, was placed under a national moratorium in 2010 following political and public opposition (MoEF, 2010). Similarly, GM mustard, developed to boost hybridization efficiency and oilseed yields, has remained stuck in regulatory limbo despite multiple expert approvals (Kumar et al., 2020). Several factors contribute to India’s regulatory caution. Public skepticism, amplified by activist groups, centers on concerns about food safety, environmental risks, corporate control, and the preservation of seed sovereignty. Legal challenges and judicial interventions have further delayed decision-making, reflecting the tensions between scientific assessments, political pressures, and public perception (Kumar et al., 2020). Additionally, India’s federal structure complicates the situation, as state governments have the authority to allow or block field trials, leading to uneven implementation across regions (Choudhary and Gaur, 2021).

In 2022, India signaled a policy shift by issuing new guidelines under the Department of Biotechnology, exempting certain **genome-edited crops** (particularly those produced using site-directed nuclease technologies without foreign DNA) from the lengthy regulatory process required for transgenic GMOs (DBT, 2022). This alignment with global regulatory trends seen in countries such as Argentina, Japan, and the United States opens the door for the development of genome-edited crops tailored to India’s climatic and agronomic challenges (Zaidi et al., 2019; Jaganathan et al., 2018). Indian public-sector institutions, including the Indian Council of Agricultural Research (ICAR) and leading agricultural universities, are increasingly focusing on genome editing to address issues like drought resilience, pest resistance, and nutritional enhancement (Adli, 2021). Nevertheless, India’s regulatory framework continues to face challenges, including bureaucratic delays, a lack of clear timelines, limited private-sector confidence, and weak public engagement mechanisms (Kumar et al., 2020). Strengthening public communication, fostering stakeholder dialogue, and streamlining regulatory approvals are essential for balancing innovation with environmental safety and socio-economic equity (Macnaghten et al., 2015). Given the country’s urgent needs for climate adaptation, food security, and rural development, an agile, science-based regulatory system is critical for harnessing the potential of modern biotechnologies. India’s GM regulatory framework is at a pivotal point. While the country has demonstrated scientific capability and agricultural need, unlocking the full potential of GM and genome-edited crops will depend on adaptive reforms, transparent governance, and a balanced approach that integrates innovation with safety and public trust. A strengthened Indian regulatory landscape will not only shape domestic agricultural outcomes but also influence India’s leadership position in the global biotechnology arena.

1. **Socio-Economic and Ethical Considerations**

One of the central socio-economic concerns revolves around the distribution of benefits and access to GM technology. Proponents argue that GM crops, such as insect-resistant cotton and herbicide-tolerant soybean, have delivered substantial benefits to farmers, particularly in developing countries where yield gains and reduced input costs can significantly improve household income (Brookes et al., 2020). Empirical studies in India, China, and South Africa have shown that smallholder farmers planting GM crops often experience higher profits and lower pesticide exposure compared to non-GM counterparts (Kouser et al., 2011). In India specifically, Bt cotton has been hailed as a transformative technology, contributing to increased national cotton yields, reduced pesticide-related health risks, and improved rural incomes, especially in Maharashtra, Gujarat, and Andhra Pradesh (Gruère et al., 2012). However, critics point out that the high cost of GM seeds, combined with dependency on commercial seed companies, can exacerbate inequalities among farmers, particularly marginal and resource-poor producers (Glover et al., 2010). Closely linked to economic concerns is the issue of intellectual property rights (IPR) and seed sovereignty. The patenting of GM traits by multinational corporations has led to debates over farmers’ rights to save, exchange, and reuse seeds—practices historically integral to agricultural communities (Kloppenburg et al., 2004). In the Indian context, controversies around seed pricing, technology fees, and licensing agreements (such as the disputes involving Monsanto’s Bollgard cotton) have fueled public debates about the balance between incentivizing innovation and protecting farmer rights. While companies argue that IPR protections are necessary to recoup research investments and stimulate innovation, farmer advocacy groups warn that over-concentration of seed markets in corporate hands can erode local autonomy and threaten agrobiodiversity (Howard et al., 2015).

On the ethical front, GM crops raise fundamental questions about human intervention in natural systems. While many scientists argue that genetic modification is a continuation of centuries of agricultural improvement, critics perceive it as an unnatural manipulation that carries unpredictable long-term consequences (Thompson et al., 2007). Ethical debates extend to issues of food labeling and consumer choice, with surveys showing that many consumers, particularly in Europe and increasingly in urban India, prefer clear labeling of GM foods to allow informed decision-making (Eurobarometer et al., 2010). Ethical frameworks also emphasize the need for transparent public engagement and consent, particularly when introducing GM crops into culturally or ecologically sensitive regions, such as India’s diverse agro-ecological zones and tribal lands (Macnaghten et al., 2015). Furthermore, biosafety and environmental justice concerns highlight the need for inclusive governance. In India, environmental groups have raised alarms about the potential gene flow from GM crops to wild relatives, especially for native crops like brinjal and mustard, as well as concerns about non-target impacts and the development of resistant pests or weeds (Hilbeck et al., 2015). Importantly, ethical analysis stresses that the burdens and risks of new technologies should not disproportionately fall on vulnerable communities or ecosystems, aligning with principles of distributive and environmental justice (Rawls et al., 1971).

Recent advances in genome editing technologies such as CRISPR/Cas9 have rekindled many of these debates, as they blur the lines between traditional GMOs and newer, potentially transgene-free modifications (Lema et al., 2019). While regulatory bodies in countries like the U.S. and Argentina have moved to exempt certain gene-edited crops from stringent GMO regulations, ethical questions persist about transparency, public consent, and the pace of technological change (Ishii et al., 2019). In India, the Department of Biotechnology’s 2022 guidelines for genome-edited plants represent a significant policy milestone, opening the door for domestic researchers to develop stress-resilient, nutrient-enriched, and region-specific crops with fewer regulatory hurdles—although societal and ethical acceptance remain critical factors for deployment. GM crops offer significant promise for addressing global and national agricultural challenges, but their socio-economic and ethical dimensions cannot be overlooked. Addressing these concerns requires interdisciplinary collaboration, inclusive policymaking, and the development of governance frameworks that balance innovation with equity, transparency, and public trust. Only by integrating scientific, social, and ethical perspectives can societies harness the full potential of GM crops while minimizing harm and maximizing shared benefits, particularly in complex agricultural environments like India.

1. **Future Prospects and Challenges**

The future of genetically modified (GM) crops is intertwined with the global challenges of ensuring food security, adapting to climate change, and achieving sustainable agricultural systems. Advances in biotechnology, particularly in genome editing, synthetic biology, and multi-omics integration, hold immense potential for reshaping the agricultural landscape (Qaim et al., 2020). For India, where agriculture supports nearly 60% of the population and faces mounting pressures from water scarcity, soil degradation, and climate variability, GM technologies represent a powerful opportunity to improve resilience and productivity. Already, genome editing approaches are being explored in Indian crops such as rice, wheat, and mustard to develop drought tolerance, salinity resistance, and enhanced micronutrient content (Zaidi et al., 2019).

On the technological front, next-generation genome editing tools such as CRISPR/Cas systems, base editing, and prime editing offer unprecedented precision in modifying plant genomes (Chen et al., 2019). These tools can create crop varieties with enhanced drought tolerance, improved nutrient-use efficiency, resistance to emerging pests and diseases, and even biofortification to address micronutrient deficiencies (Zsögön et al., 2017). For India, this is particularly promising, as it could support the development of crops adapted to diverse agro-climatic zones, benefitting both large-scale and smallholder farmers (Jaganathan et al., 2018). Another promising avenue is synthetic biology, which enables the design of novel metabolic pathways and synthetic gene circuits, opening the door to entirely new agricultural functions, such as nitrogen fixation in cereals or the production of high-value pharmaceuticals in plants (Erb et al., 2017). Integrating multi-omics approaches, such as genomics, transcriptomics, and metabolomics, can further accelerate precision breeding and trait discovery, tailoring crops to local environmental and socio-economic conditions, including India’s varied and stress-prone landscapes (Ricroch et al., 2017).

Despite these advances, regulatory challenges remain a key bottleneck. Regulatory systems worldwide vary widely, with some countries (e.g., Argentina, Japan, and the U.S.) adopting product-based assessments that exempt certain genome-edited crops from GMO regulations, while others (e.g., the European Union) maintain stringent, process-based frameworks (Whelan et al., 2020). India’s regulatory landscape has recently shown signs of flexibility, especially with its genome editing guidelines, but delays in decision-making, legal disputes, and public mistrust remain persistent hurdles (Turnbull et al., 2021). Public perception and trust represent another major challenge. Despite extensive scientific evidence supporting the safety of GM crops, public skepticism persists, driven by concerns about environmental risks, corporate control, and ethical acceptability (Funk et al., 2020). In India, media narratives, political campaigns, and activist mobilizations have often amplified fears around GM foods, underscoring the need for transparent communication, inclusive stakeholder engagement, and meaningful public participation in decision-making processes (Macnaghten et al., 2015).

Socio-economic barriers also pose significant hurdles. Smallholder farmers in developing countries may face challenges accessing GM technologies due to high seed costs, inadequate extension services, or lack of infrastructure (Glover et al., 2010). Ensuring that the benefits of GM innovations are equitably distributed will require supportive policies, public-sector investment, and capacity-building efforts tailored to local contexts, particularly in India where marginal farmers dominate the agricultural landscape (Kouser et al., 2011). Finally, ecological considerations must not be overlooked. While GM crops can reduce pesticide use and improve land-use efficiency, concerns about gene flow, pest resistance, and impacts on non-target organisms highlight the need for robust environmental monitoring and adaptive management strategies (Hilbeck et al., 2015). Balancing innovation with ecological stewardship will be critical to ensuring the long-term sustainability of GM agricultural systems, especially in a country as ecologically diverse as India.

1. **CONCLUSION**

In conclusion, the future of GM crops holds tremendous potential to contribute to resilient, productive, and sustainable food systems in India and beyond. However, realizing this potential will require coordinated efforts across science, policy, and society to navigate the complex challenges and ensure that technological advances translate into broad-based, socially acceptable, and environmentally responsible benefits.

**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 the writing or editing of this manuscript.

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